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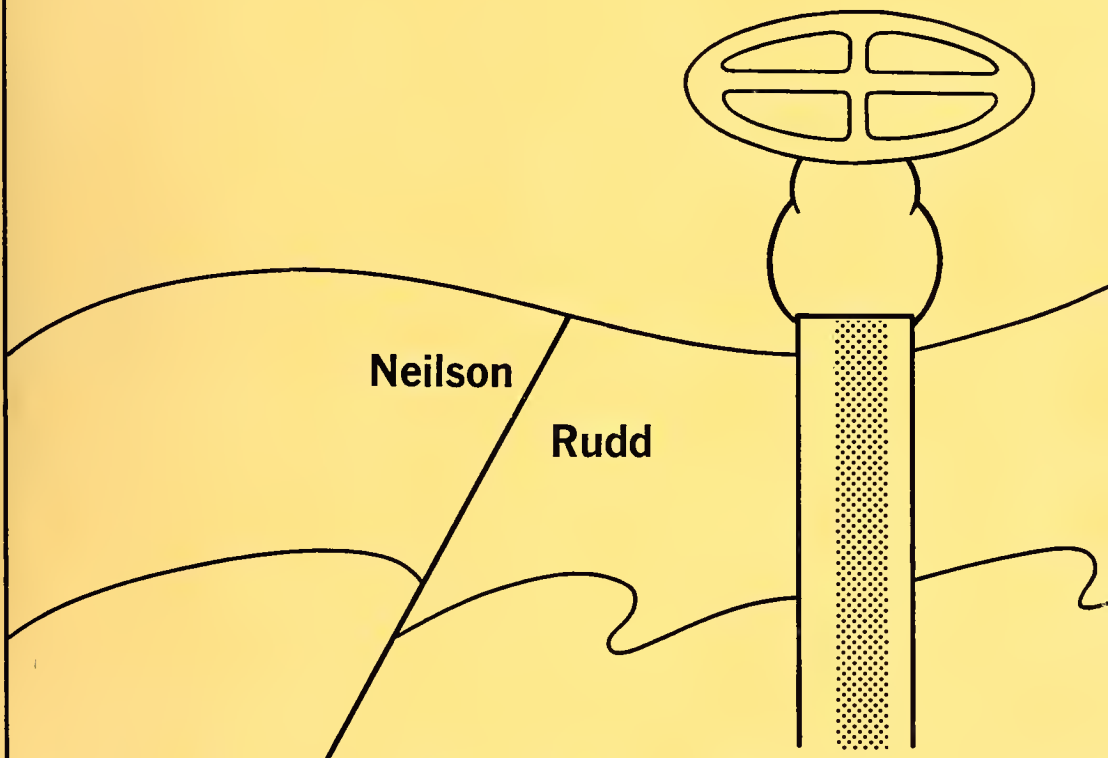
Environmental Geology Report 3
1972

Subsurface Liquid Waste Disposal and Its Feasibility in Pennsylvania



COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF ENVIRONMENTAL RESOURCES
BUREAU OF
TOPOGRAPHIC AND GEOLOGIC SURVEY
Arthur A. Socolow, State Geologist

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ENVIRONMENTAL GEOLOGY REPORT 3

Subsurface Liquid Waste Disposal and Its Feasibility in Pennsylvania

by Neilson Rudd
Cooperating Geologist

PENNSYLVANIA GEOLOGICAL SURVEY

FOURTH SERIES

HARRISBURG

1972

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PREFACE

In a state such as Pennsylvania, growing in both population and industry, the problems of environmentally aeeeptable waste disposal have beeome a serious eoneern. Partieularly troublesome are industrial liquid wastes, which by their very nature are highly mobile and diffieult to store and treat at the surfaee. One solution whieh has been eonsidered is injection of these liquid wastes into the pore spaee of deeply buried rock. Sueh projeets, in varying levels of teehnieal sophistieation, have been undertaken in Pennsylvania and throughout the eountry. Opinion is mixed with regard to the sueeess of individual projeets and the degree of danger to the environment whieh results. Beeause of the pressures for a satisfaetory solution to liquid waste disposal and the eurrent interest in doing so by injeetion into the deep subsurfaee, deeisions will be necessary on the part of industry, government, and the publie. This report provides a baekground for sueh deeision making.

The earth is not as stable and as unehanging nor is roek as "solid" as many people believe. In those segments of the earth's erust whieh are most suitable for waste injeetion, native fluids are almost universally present and often in limited eontinuity throughout broad areas. The roek and its contained fluids reaet as a eomplex physieal, meehanieal, and ehemical system. Ultimately, deep well disposal projeets must be judged in terms of their probable short and long term effeets upon this roek/fluid system.

One of the diffieulties in dealing with the subsurfaee is that our knowledge of it is often indireet and ineomplete. It is important, therefore, that all available data be earefully evaluated and that all sourees of new information be employed to their maximum effeetiveness. It is equally important that projeets dealing with the subsurfaee, partieularly those whieh carry any risk of environmental damage, incorporate in their design philosophy a realistie appreeiation of the limitations of subsurface interpretation by providing means for eontinuing surveillanee and control of the projeet. Two basie types of subsurfaee liquid disposal operations are defined: the elosed system providing permanent disposal, and the open system providing temporary storage with an opportunity for attenuation or neutralization of the waste's potentially harmful charaeteristies. Identifieation and exploitation of disposal prospects of these types have speeifie data requirements, often quite different from oil and gas operations and hydrology.

The geology of the Commonwealth of Pennsylvania may be generally divided into three provinees of whieh only the Appalaehian Plateaus in the western and northern portion of the state offer signifieant opportu-

nities for deep well waste disposal. Elsewhere, the frequency of sufficiently porous and permeable rock units is exceedingly limited or their intimate association with the ground-water supply renders them unsuitable for the disposal of wastes. The complexity of the geology of Pennsylvania creates particular difficulty in developing truly reliable interpretation of the subsurface without extensive exploratory testing and evaluation.

The number of geologists engaged in oil and gas exploration and development, underground gas storage, subsurface waste disposal, and geohydrology who have contributed to the preparation of this report by critical reading, discussion, suggestions, and in many other ways is too large to enumerate. Particular appreciation, however, is expressed to Dana R. Kelley, Alan R. Geyer, and William G. McGlade of the Pennsylvania Geological Survey for their encouragement, helpful suggestions, and assistance in obtaining necessary data.

In this regard, and in all other aspects of this report, the interpretations and opinions presented are those of the author and responsibility for any errors, omissions, or misinterpretations must also be mine.

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Subsurface Liquid Waste Disposal and Its Feasibility in Pennsylvania

by

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ABSTRACT

Basic principals of deep well liquid waste disposal are discussed in Part I of this report. Relevant concepts of geology, hydrology, and reservoir engineering are presented in terms which the non-geologist can understand. In particular, the distinction is made between "closed" and "open" reservoir systems and in the case of the "open" system, the importance of considering the total rock/fluid system is stressed.

Two basic types of subsurface liquid waste disposal operations are defined in Part II: the closed system providing permanent disposal, and the open system providing temporary storage with an opportunity for attenuation or neutralization of the waste's potentially harmful characteristics. In that the identification and exploitation of disposal prospects of these types have specific data requirements, a number of "checklists" are suggested to assist those responsible for disposal site selection, implementation, and regulation. Methods by which environmental risks may be minimized are noted both in the checklists and in the text of Part II.

The final portion of the report, Part III, deals specifically with the feasibility of deep well liquid waste disposal in the Commonwealth of Pennsylvania. Northwestern Pennsylvania has potential areas for deep well liquid waste disposal. However, the limited occurrence of adequate reservoirs, the complexity of the Commonwealth's geology, and the high degree of dependence of the population upon subsurface resources will require that subsurface waste disposal projects be subject to very careful exploration, evaluation, and operation.

PART I — PRINCIPLES

There would be no need to consider the injection of liquid wastes into deeply buried rock were the wastes tolerable in the surface environment. Since they are not, the objectives of subsurface waste disposal must be either permanent isolation of the effluent from man's environment or temporary storage of the waste pending attenuation of its undesirable aspects.

Whatever the approach, a project cannot be considered acceptable unless the following questions can be answered with a high degree of certainty:

(a) Where is the injected liquid going? — initially, and for so long as it carries the potential for hazard or nuisance?

(b) What will be the effects, both direct and indirect, present and in the foreseeable future, upon our environment?

While to provide suitable answers for such questions requires a very substantial effort, any less thorough an evaluation must be recognized as simply "sweeping the dirt under the rug," a temporary expedient which is both morally and economically irresponsible.

This is not to say that alteration of the surface and geological environment should not be permitted, nor is it to say that some uncertainty of outcome cannot be tolerated. On the contrary, the pressing demands of society often justify some risk.

What *is* required is the fullest possible investigation into the effects of waste injection upon the geological environment, careful estimation of the probability and potential magnitude of these effects, and evaluation — by industry, the public and government — of the merits of each project relative to its environmental risk.

The purpose of this part is to review some of the critical aspects of the geological environment which may be affected by waste injection.

THE GEOLOGICAL ENVIRONMENT

Geological Processes and Materials

The earth's crust is a complex physical and chemical system, a dynamic system involving many elements and forces in delicate and often unstable equilibrium. Since the injection of waste materials into the subsurface must result in alteration of this system, it is very important to be aware of certain geological principles and be on guard against several popular misconceptions.

The Continually Evolving Earth

The earth is never still.

The crust of the earth on which we live and from which we draw our mineral resources may be visualized as a superficial layer of slag floating upon a mobile, viscous layer known as the mantle. Pieces of this crust or slag are constantly in motion, moving from place to place and being forced upward or drawn down into the mantle.

Not only is the earth subject to constant internal movement, but its materials, the rocks themselves, are in a process of continuous change. Igneous rocks are derived from the cooling of molten mineral solutions at the surface such as volcanic lavas and other extrusive materials, or at depth as massive, dense intrusive formations. With the possible exception of cavities in buried lava flows, *igneous rocks do not provide the characteristics desirable for liquid disposal.*

The upper surface of the crust is subject to erosion and chemical decomposition. The debris from the breakdown of crustal materials is transported by wind, water and gravity, as particles or in solutions, eventually to be redeposited, usually in seas and other bodies of water. The rock which results from solidification of this material is called sedimentary. It is this family of rock types that are concerned in subsurface waste disposal in Pennsylvania.

A third broad category of rock types, the metamorphic, is altered igneous or sedimentary rock. These metamorphic rocks are dense and nonporous and thus unsuitable as a site for waste disposal.

Deposition of Sedimentary Rocks

Sedimentary rocks are deposited in relatively thin, laterally extensive layers.

Each layer reflects the type of material available and the physical conditions prevailing at the time of deposition. In broad, shallow seas far removed from sources of rock debris, limestone may be chemically precipitated. Where granular material is provided from nearby land masses and where currents and wave action are strong, sandstone may be laid down near the shoreline. Fine-gained material may be deposited as shale. If the adjacent landmass is slowly submerging, each depositional environment will gradually shift shoreward with time, depositing sandstone, overlain by shales and limestones. If the landmass is emerging the sequence is reversed.

These sequences may appear orderly (Fig. 1A) but they seldom are. Variations of rock types in changing depositional environments are often duplicated on a smaller scale within the large rock unit (Fig. 1B). A brief interruption in the supply of coarse sediment or the diversion of a distributary channel may result in deposition of a thin layer of clays. A severe storm may build up or tear down a sand spit or bar. The growth of a coral reef may entrap granular material on one side while excluding it on the other.

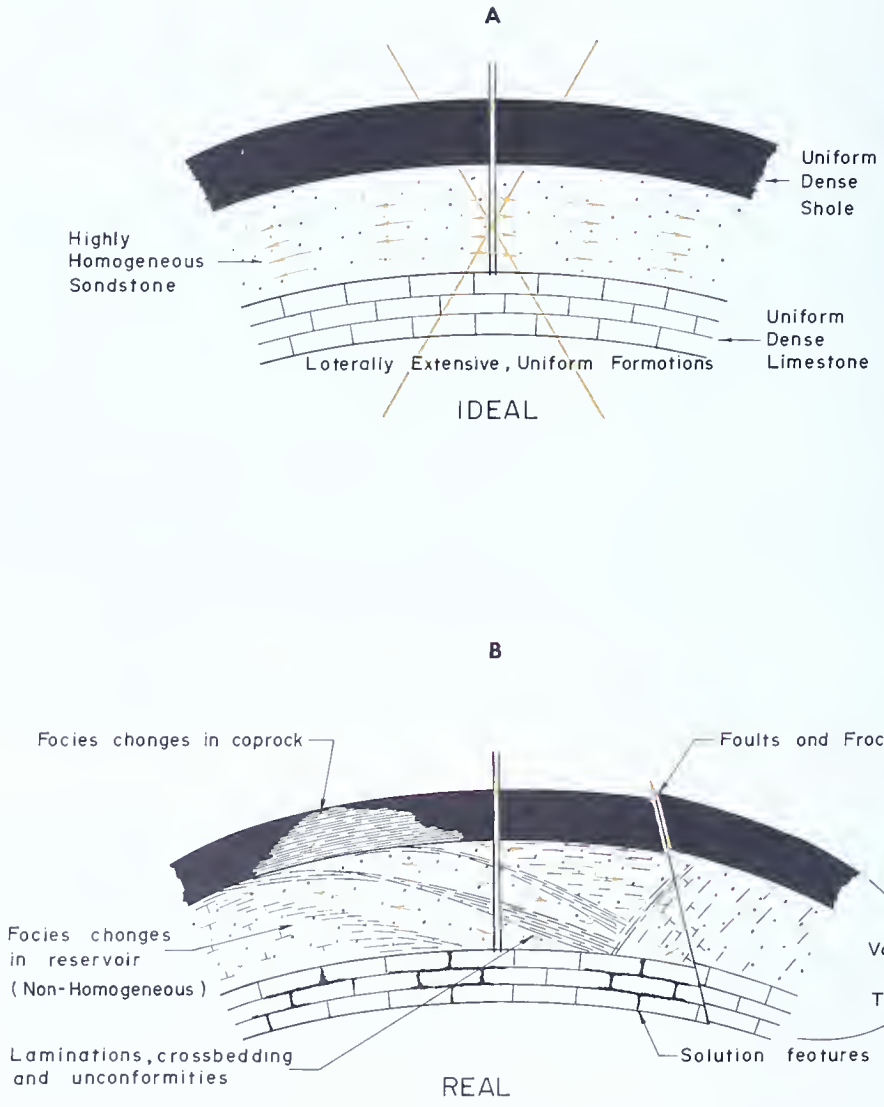


Figure 1. Ideal vs. real subsurface conditions.

Other agencies affect the deposition of sediments, either as a part of general shoreline shifts or independently. Streams or submarine currents may produce elongate, wandering depositional patterns following their channels or broad fan-shaped deposits of intricately intermixed sediments in deltaic areas. Submarine landslides may stir up sediments into a heavy aqueous suspension which flows down the continental slopes with astounding rapidity and force, carrying with it immense volumes of sediment.

A specific type of sedimentary rock, evaporites, of particular significance to disposal operations, results from the "drying-up" of ancient seas.

When evolution of the earth's crust cuts off the sources of fresh water and restricts the circulation of sea water, evaporation gradually concentrates the dissolved minerals until the brine becomes saturated and precipitation occurs. By this process thick accumulations of highly homogeneous and dense evaporites, notably salt, may form.

Lithification of Sediments

As they are buried and compacted, sediments become bonded together by friction, by the addition of other minerals as intergranular cement, or by intergrowth. They acquire a measure of coherence and rigidity and become rock. Most sedimentary rocks contain voids or pore spaces between their grains and crystals because a portion of the water in which the sediments were deposited is entrapped. Sometimes the grains are irregular in shape and strong enough to resist deformation during compaction, resulting in voids or pore spaces between grains or crystals.

As the sediments become rigid they become capable of transmitting stress but also become susceptible to failure. Under the weight of accumulating load, the portion of the crust upon which the sediments are deposited may bend downward and result in compression, folding, fracturing and faulting. Even when relatively undisturbed, the rock may develop joints, parallel sets of nearly vertical fractures formed without movement.

If a portion of the rock is uplifted to the surface or near-surface, it becomes subject to erosion or chemical decomposition which may remove some of its constituents, redeposit others, and locally change the character of the rock. Deeper burial may result in further compaction and expulsion of native water, altering both the sediments compressed and those through or into which the expelled waters are displaced.

Sedimentary rock sequences are rarely truly homogeneous in internal structure or lithology (Fig. 1).

Certain stratigraphic units may be rendered locally impermeable by variations of deposition or by secondary processes while others, impermeable at deposition, may be so altered by solution activity or structural breakage as to develop extensive permeable zones.

It is important that those concerned with subsurface waste disposal recognize the complex lithology of sedimentary rocks and particularly that the classification of a stratigraphic unit under a single formation name does not necessarily imply homogeneity or continuity of lithologic characteristics.

Natural Fluids in Rock

Natural fluids are active chemical and physical components of the rock-fluid system.

With the rare exception of fluids in relatively rapid motion, the liquids and gases within subsurface pore space are in chemical equilibrium with the rock, with adjacent fluid components, and with the existing conditions of temperature and pressure.

The rock-fluid system is subject to the Law of Chemical Equilibrium and to Le Chatelier's Principle under which any modification of the system may produce compensating changes in pressure, temperature and composition.

Most native waters in rock are brines containing high concentrations of sodium chloride together with a wide variety of other soluble salts. In general, the deeper the formation, the more concentrated the brine. This may be the result of increased solubility under high conditions of temperature and pressure or of dilution by surficial water. However, neither of these mechanisms can satisfactorily account for the magnitude and range of concentration observed. A more adequate and satisfactory explanation lies in the osmotic filtering of brines expelled from sediments during compaction. The fine-grained rocks, particularly those composed of clay minerals, act as a semi-permeable membrane and permit the passage of water while excluding certain ions (osmotic filtering). The higher concentration of salts is then the result of the "filtration" of the larger volume of water squeezed out of the deeply buried rock. The selective nature of osmotic filtering may explain the variation in subordinate mineral content, particularly calcium, in subsurface brines.

The actual volume of occurrence of other formation fluids such as hydrocarbons, carbon dioxide, or helium is so minor as to be practically negligible except for indirect effects upon the behavior of other fluids. Free gas effectively raises the compressibility to the fluid system, an important factor when we come to consider injection or withdrawal. Oil or gas may create a local impermeable barrier to the flow of aqueous liquid due to their immiscibility (inability to mix).

The most important aspect of rock fluids is their chemical properties with relation to their environment.

Since these fluids have been in prolonged, intimate contact with the rock, they may be presumed to be saturated with regard to most soluble mineral constituents. The equilibrium thus attained is precarious, not only in terms of relative solubility, but also in relation to reaction favored by changes in temperature and pressure. Any change in composition of the fluid or in the physical environment may result in precipitation of solid compounds, increased dissolution of the host rock, or increases or decreases in pressure or in temperature.

The Rock-Fluid System

The fluid phases saturate the system, filling all pores, fractures and other voids below the water table. No void is truly "empty."

The sedimentary rock environment may be considered as a multiphase system with rock constituting the solid phase and water (rarely oil) as the liquid phase. A third phase, gas, is infrequently present in quantities exceeding its solubility in the liquid phase.

The solid elements of the system, the rocks themselves, may be classified according to their effects upon fluid flow. Rocks through which fluids flow with ease are termed reservoir rock by the oil and gas industry or aquifers in hydrogeology.

Rocks tending to restrict the flow of fluids are classified as caprock or as aquicludes or aquitards depending upon whether the flow is absolutely excluded or only retarded.

Continuity of the Fluid Phase

Few sedimentary rock types are impermeable in the sense of flow between particles and crystals, and when permeability along structural discontinuities (bedding planes, fractures, faults) is considered, a condition of absolute impermeability must be regarded as rare.

Elementary geological textbooks usually present the picture of solid, continuous, and impervious "caprock" units controlling the accumulation of oil and gas. This is an over-simplification from the point of view of subsurface waste disposal. A similar misconception regarding the impermeability of rock may be implied by the term "aquiclude" as used in hydrogeology.

The recognition of the pervasiveness and continuity of the liquid phase is of such importance to waste disposal as to require thorough clarification of these apparent discrepancies in concept.

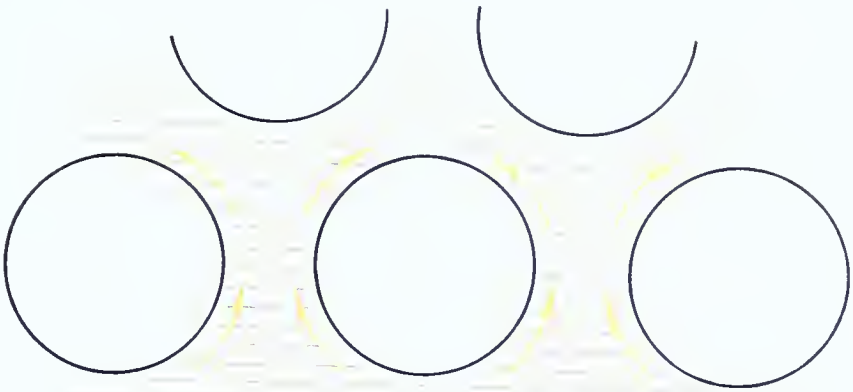
The caprock of an oil or gas accumulation depends upon capillary phenomena and the immiscibility of liquid or gaseous hydrocarbons with water, rather than upon impermeability of the rock. Water retained by capillarity between water-wet grains will not be displaced until the pressure differential across the water/hydrocarbon interface exceeds the interfacial tension. In fine-grained materials where the diameter of the interface is very small, this critical pressure – the threshold pressure – may be measured in thousands of pounds per square inch. Thus, impermeability to oil or gas has no meaning per se with relation to the flow of aqueous liquids (Fig. 2).

Most oil and gas accumulations are gravitationally entrapped due to the segregation of the lighter hydrocarbons above water. Then impermeability of the caprock, even if proven relative to water, is only valid in the vertically upward sense and for immiscible fluids which will not diffuse downward or outward in the native brine.

The concept of the impermeable aquiclude in ground water is valid for short time periods, for years or decades, and for low pressure differentials, but it is rarely accurate when extended to centuries or when small amounts of water going through are significant. Recently the term "aquitard" has been introduced to describe formations providing less than absolute restriction of flow. When used in connection with waste disposal where slight flows may be critical, more formations will function as aquitards than as aquicludes.

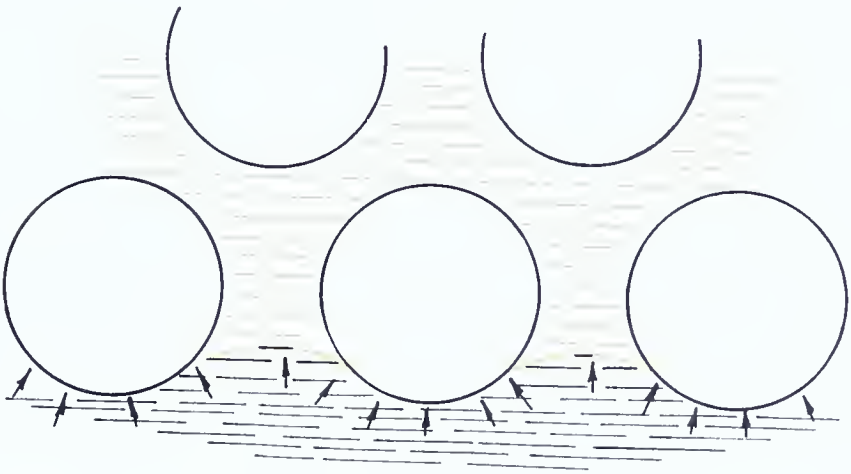
Evidence of Continuity

That absolute impermeability is an uncommon condition does not mean that fluid flow within the crust is not constrained. It does mean that the constraints controlling the direction and rate of flow must be regarded as relative and evaluated according to the actual conditions of time, pressure, composition, and other factors encountered or anticipated in a given project at a specific location.



SINGLE FLUID PHASE

NO BARRIER TO FLOW



TWO IMMISCIBLE FLUID PHASES

NON-WETTING PHASE IS BARRED FROM PORES BY SURFACE TENSION

Figure 2. Impermeability due to threshold pressure.

The pressure of fluids occurring within the upper portion of the earth's crust closely approximates the pressure which would be exerted by a continuous column of water extending from a point at depth to the overlying water table. This is true despite the fact that the rock units in which the fluid pressure is measured may have been uplifted or downthrown from greatly different pressure regimes. This fact is perhaps the most persuasive evidence of the rarity of absolute impermeability. Fluid pressures are not commonly "fossilized," entrapped and "frozen" at the pressure under which the sediments were first deposited or lithified. They show a continuous adjustment to changing depths below the water table. There are exceptions. Among the most notable exceptions are several gas fields in the Oriskany sandstone of Pennsylvania and West Virginia.[1]

Evidence of vertical continuity of the liquid phase is seen in the concentration of salts, particularly sodium chloride, in subsurface waters. Where vertical liquid continuity and flow are rare or nonexistent, the concentrations of salts in subsurface waters should bear no relationship to depth but rather should be controlled exclusively by the mineral content of the rock itself and the brine in which it was deposited. Yet, throughout the sedimentary basins of the world, salinity of native water decreases towards the surface.

This may result from intermixing of surficial fresh water but is largely the result of selective filtration of the original brines upon being expelled upward through the overlying rock during late stages of compaction. In either instance, vertical continuity is implied and in the latter case the flow must be through inter-pore permeability rather than fractures to achieve the effect of filtration.

The petroleum industry also provides negative evidence of the rarity of truly impermeable rock units. Exploration reveals geological situations which, from all available evidence, should have provided a trap, yet have failed to do so. Residual quantities of hydrocarbon indicate that the deficiency lay not in the supply of oil and gas but in the permeability of the caprock.

When dealing with the flow of fluids through rock, it may be useful to conceive of a region of sedimentary rock as a three-dimensional mosaic (Fig. 3) imperfectly fitted, and subject to continued deforma-

[1] While the discussion in this and the following Part II of this report are intended to be general in scope, it should be noted that the Paleozoic rocks of the Appalachian Plateau in Pennsylvania and adjacent states are exceptionally dense and thus more likely to contain apparently wholly isolated reservoirs of the kind noted above. How pervasive such conditions are is the subject of some scientific debate but their existence seems undeniable.

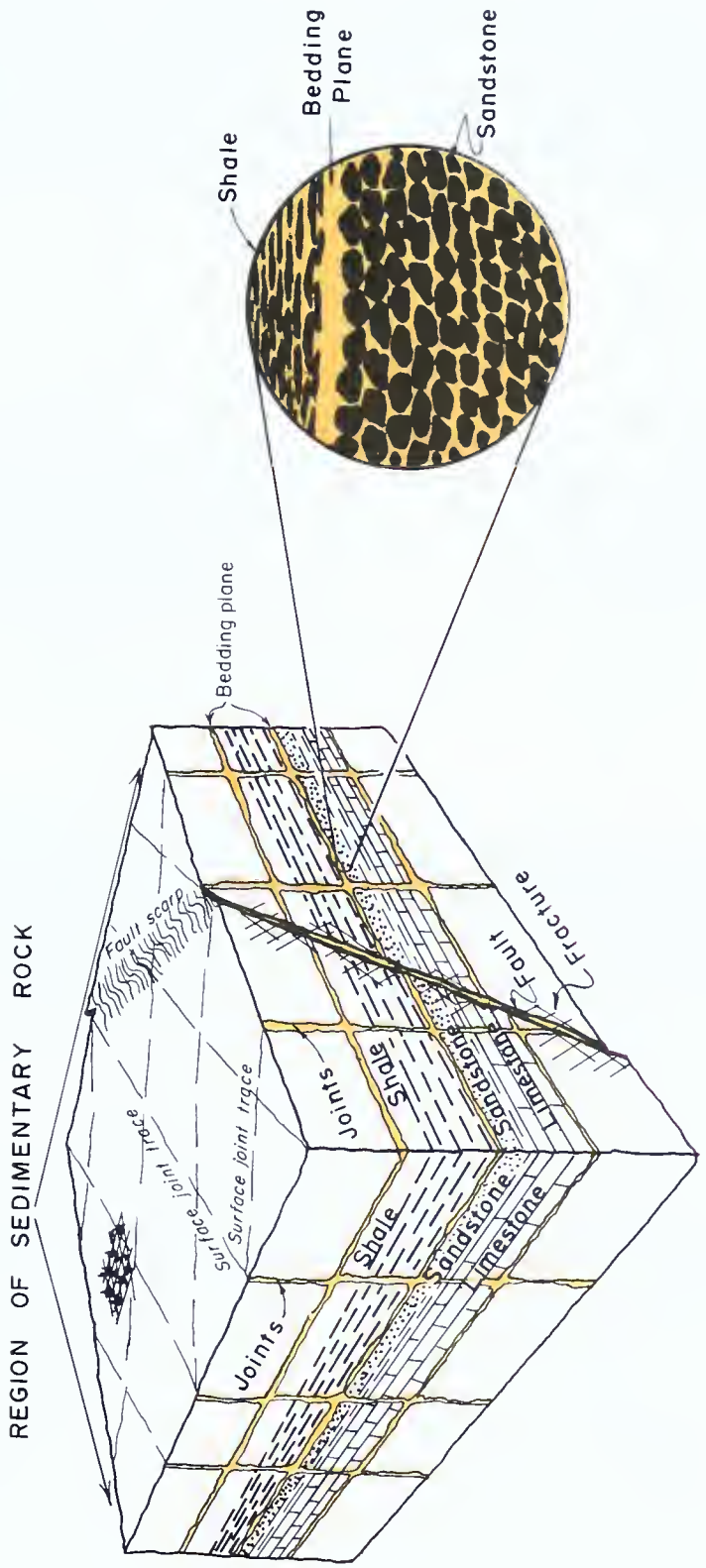


Figure 3. The rock/fluid system.

tion. This model shows a similarity of materials in any horizontal layer but considerable variation in the vertical sequence of materials. All but the uppermost portion of the model is saturated with fluid. The joints in the mosaic may be sealed or they may remain unsealed and become enlarged by erosion or solution.

In summary, the sedimentary geological environment is a rock-fluid system in which the fluid phase is both extensive and continuous. As will be developed in subsequent sections of this report, the interrelation of fluid and rock modifies the behavior of both under conditions of movement and stress.

THE FLOW OF FLUIDS IN THE SUBSURFACE

Hydrology

The Causes of Flow

Fluid in a continuous system will flow from a region of high potential energy to one of lower potential. This energy may be derived from gravitation (the weight of a column of water or its "hydrostatic head") or from such external sources as the compaction of rock or artificial pumping.

The gravitational potential energy of a fluid is a function of its density and its height. If fresh water is poured into one arm of a "U"-tube (Fig. 4A), the liquid flows until it reaches equilibrium with equal column heights in both tubes. If, on the other hand, one arm is filled with fresh water and one with brine (Fig. 4B), the height of the fresh water column at equilibrium will exceed that of the column filled with the heavier brine.

Compression of sediments by gravitational or tectonic forces results in outward and upward expulsion of the native liquid. It is less evident that an inward flow may result from elastic expansion of the rock upon release of pressure either by relaxation of tectonic forces or by unloading through uplift and erosion. While the rates of flow are normally very slight, there is substantial evidence that subsurface fluids are rarely at rest.

Since the rock environment contains fluids, usually water or brine, as a continuous phase, these fluids will tend to flow to attain equilibrium and the net direction of this flow can be predicted.

It is important to recognize that while the net flow direction is predictable the actual path of fluid flow may be tortuous, following the route of least resistance.

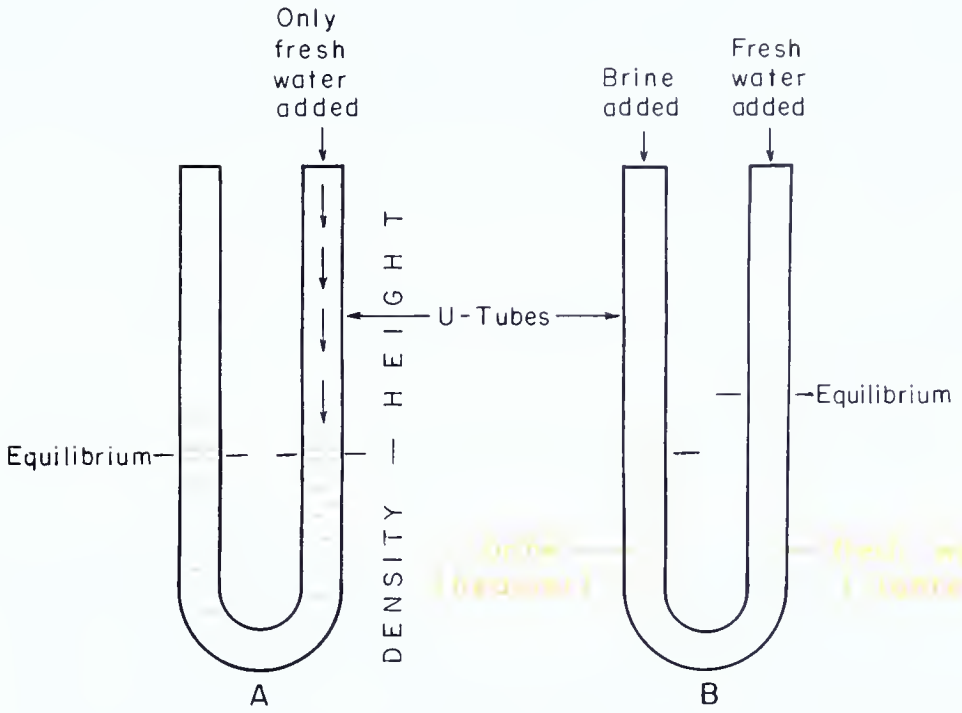


Figure 4. Hydrostatic pressure related to liquid density.

The Potentiometric Surface

If an aquifer is penetrated by a large number of wells and if each well is filled with fresh water to such a height as to exactly balance the fluid pressure within the aquifer so that no fluid movement occurs between the well and the aquifer, the elevations of the tops of all the water columns will define the potentiometric surface.

This surface may then be mapped topographically relative to sea level or some other datum (Fig. 5).

If the map reveals no variation in static water level throughout a region, it can be assumed that there is no fluid movement within the rock. If, on the other hand, there is a gradient in the potentiometric surface, it can be assumed that fluid is flowing toward the low pressure end of that gradient. The net direction of flow movement will always be at right angles to the contours and from high pressure to low pressure. Thus, the contours of the potentiometric surface in the vicinity of a well injecting liquid radially into a porous formation will be a

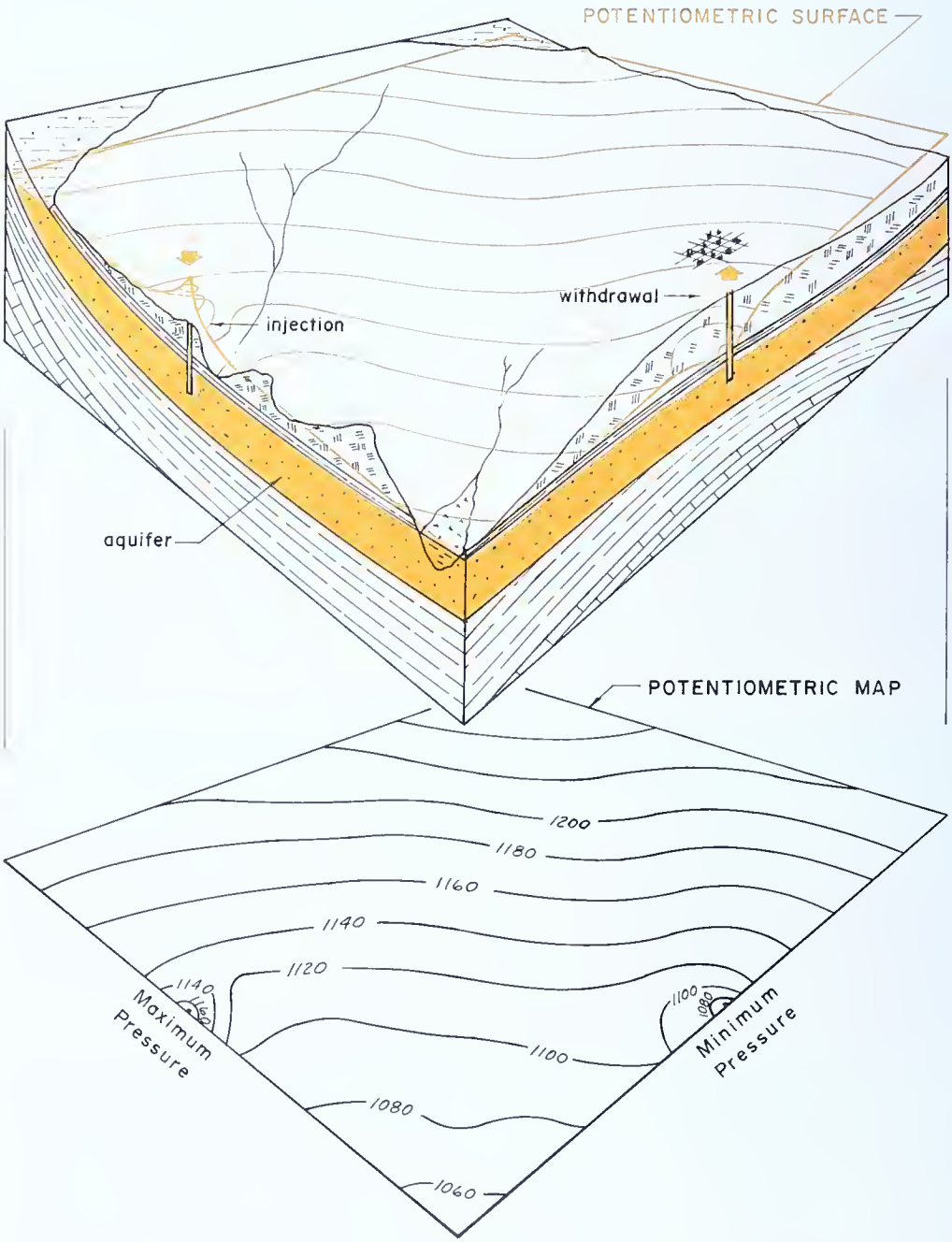


Figure 5. The potentiometric surface.

series of concentric circles with a maximum at the well location. A withdrawal well will present a similar contour pattern with a minimum pressure at the well location. The superimposition of a natural gradient upon an injection or withdrawal gradient creates distortions of the contours reflecting the complex patterns of fluid movement.

The Isopotential Surface

The potentiometric surface is a special case of a general concept in hydrodynamics, the isopotential surface, which connects all points of equal pressure. Since no pressure differential can exist on this surface, flow cannot occur within it and must always be in a direction normal to the surface.

The isopotential surface, when pressure equals zero, is the potentiometric surface, primarily useful for predicting lateral net flow, i.e., within a formation.

A series of isopotential surfaces at increasing pressure increments defines the whole hydropotential field in three dimensions, providing a more complete understanding of interformational as well as intraformational net flow tendency. Again, the actual flow pattern depends upon the path of greatest permeability and may be more complex than that indicated by the generalized flow lines inferred from broadly spaced potentiometric data.

The existence of a potentiometric difference between two points in the earth's crust does not assure flow between them; however, it does indicate the potential for flow the moment a permeable interconnection becomes available. Potentiometric studies therefore have both an immediate application in the design of a disposal project and a possible future application in guiding remedial steps should unanticipated fluid movement occur.

The isopotential surface has particular significance in the segregation of fluids of differing densities. Where a potentiometric gradient exists, the surface of contact tends to parallel this surface and may be tilted substantially relative to the horizontal (Fig. 6). Therefore, structural control of entrapment or confinement of high or low density (relative to water) fluids must be determined.

Rock Characteristics Controlling Fluid Flow

The actual paths and rate of fluid flow will be determined by the relative porosity and permeability characteristics of the rock units involved.

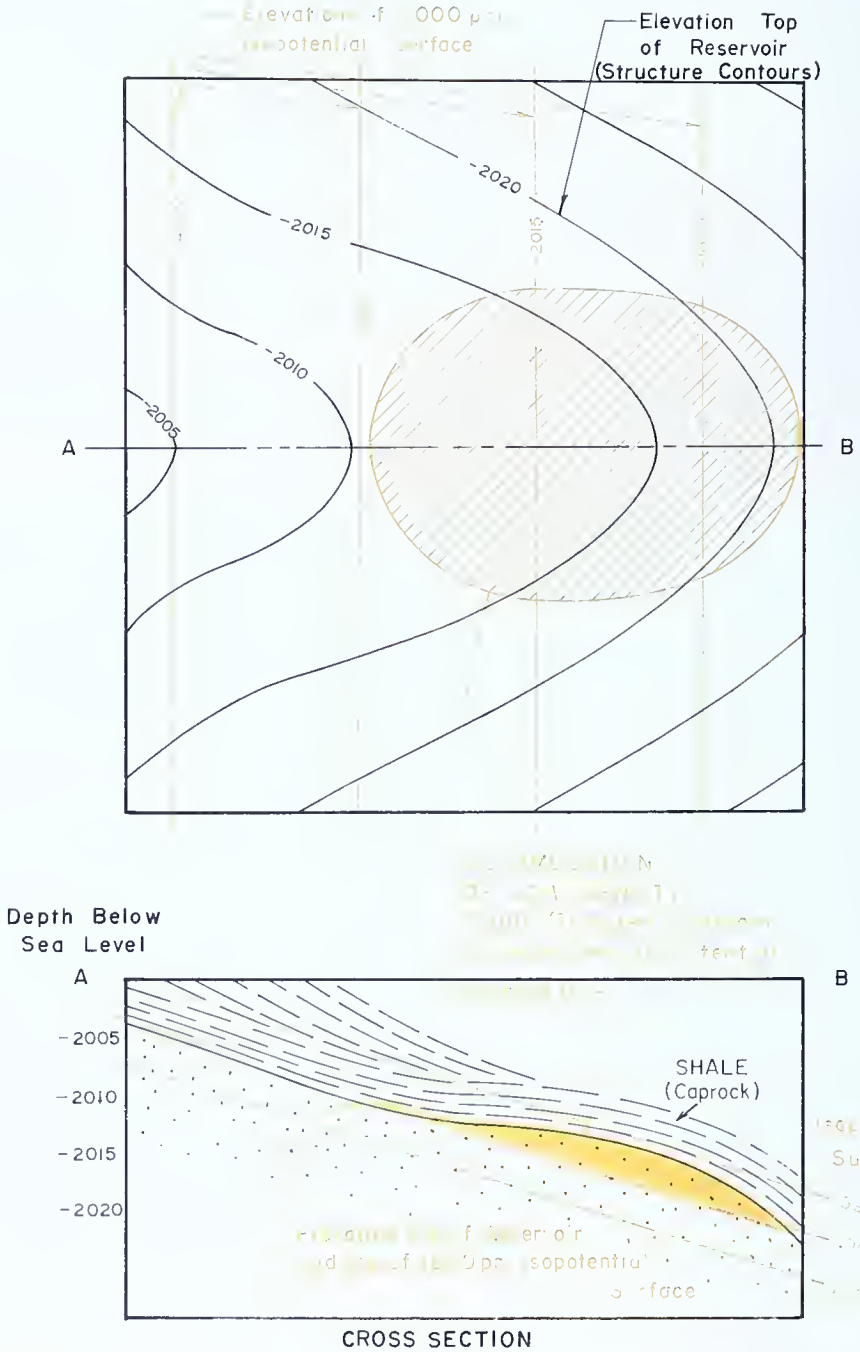
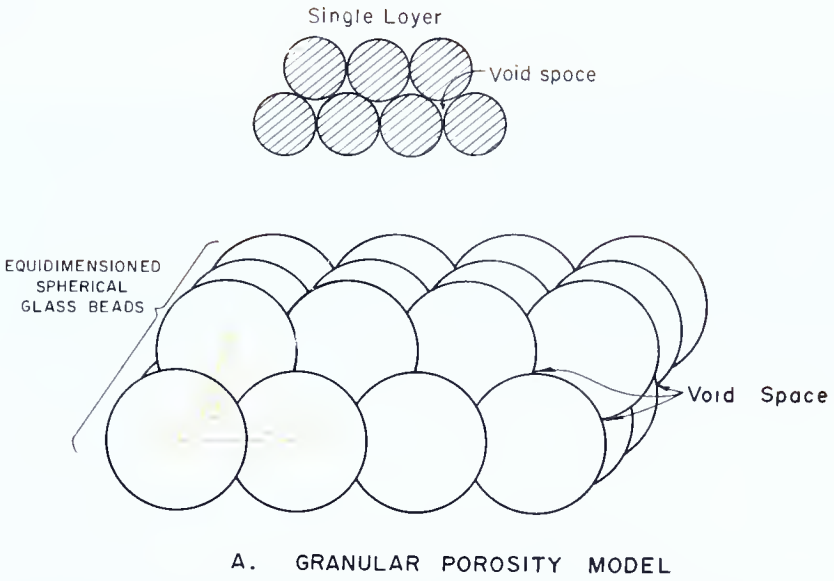


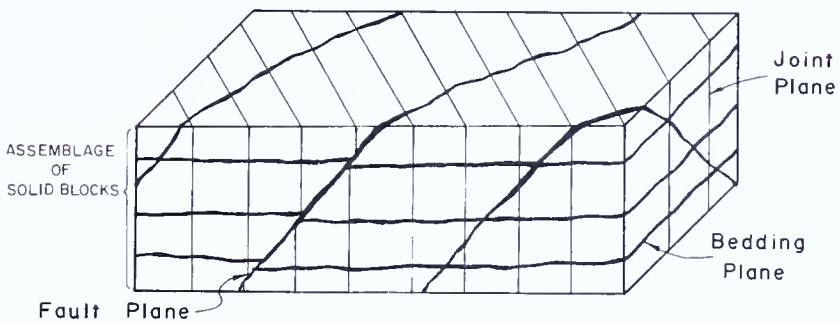
Figure 6. Hydrodynamic entrapment.

Porosity

Consider a model (Fig. 7A) consisting of a large number of equidimensioned spherical glass beads packed together to create a porous mass. The ratio of the volume of the void space between the beads to the volume of the model as a whole, expressed as percentage, is identified as the porosity.



A. GRANULAR POROSITY MODEL



B. PRISMATIC POROSITY MODEL

Figure 7. Two types of porosity systems.

The porosity will vary according to the closeness of the geometrical arrangement of beads and will be at a minimum when the "packing" of four beads forms a tetrahedron. If additional smaller beads are added to the model, some may fit within the pore spaces created by the large beads, reducing the porosity. If any additional material is added to the surface at the points of contact between the beads, cementing them together, the volume of the pore space will again be reduced by the volume of the cement added.

The degree of porosity in granular materials is controlled by the packing—the geometrical arrangement between grains, the sorting—the degree of dimensional uniformity, and the cementation—the additional minerals binding the granules together.

If a similar model constructed of Ping-Pong balls were substituted for the glass bead model, it would be an illustration of an important distinction with regard to the meaning of the term porosity. If porosity means all void space, then the porosity of the Ping-Pong model would approach 100 percent since the interior of the balls is also a void. However, if we wish to consider only the accessible, interconnected pore spaces, then the porosity would be the same for glass beads of similar geometrical packing. The two types of porosity may be identified by referring to the first as total and the second as effective.

"Blind" pore spaces (space inside a mineral grain or fragment) may be effective from the point of view of storage of fluids but they are wholly ineffective in transmission.

This granular porosity model is useful in understanding the reservoir characteristics of many lithologies, particularly sandstones. An alternative prismatic model (Fig. 7B) is useful in the study of carbonates and dense, fractured reservoirs. In this case the reservoir may be considered as an assemblage of polygonal solids bounded by plane surfaces along bedding, faults, fractures, and joints. The porosity is controlled by the degree of conformity of the surfaces of adjacent rock prisms as modified by solution, structural offset, or tensional displacement. As in the case of granular porosity, the characteristics of the reservoirs may be modified by subsequent solution and cementation.

Permeability

Ultimately our concern is with the transmission of fluids through porous rock and with the measure of the ease of fluid movement, the permeability.

Permeability may be thought of as the reciprocal of the frictional resistance to the flow of a fluid through a medium. The lower the resistance, the higher is the permeability. The unit of measurement is the darcy, which is that value of permeability which permits one milliliter of a fluid of unit viscosity (approximately equal to water) to flow a distance of one centimeter through a cross-sectional area of one square centimeter in one second under a pressure drop of one atmosphere. The darcy is too large a unit for reservoir studies. The millidarcy (1/1000th of a darcy) is the customary unit for these purposes.

Resistance to flow of a fluid through a porous material is primarily due to friction between the fluid and the surface of the pores and apertures through which it is flowing. A model of tetrahedrally-packed Ping-Pong balls has the same percentage porosity (effective) as does a model of tetrahedrally-packed very small glass beads. The cross-sectional area of permeable channels running through the models would be identical. However, in the glass bead model the exposed surface area of the grains is much greater than that in the Ping-Pong ball model and the permeability would be much less.

If the porous material is poorly sorted—that is, contains small grains within the pore spaces between large grains—the surface area is increased, resulting in further reduction of permeability. Excessive cementation further increases the surface area and further restricts the openings between grains, reducing permeability.

If a number of the apertures between pores are totally obstructed by cement or other material causing the fluid to follow a tortuous path, the permeability is reduced not only in proportion to the percentage of pore spaces closed off, but also in proportion to the additional length of the flow path. Finally, for a given pressure drop across the core, the permeability to compressible fluids, particularly gases, is reduced more when the intergranular apertures become very small due to the compression of the flow medium upstream of the aperture. This effect, the Klinkenberg effect, is important when evaluating low permeability reservoirs from gas production records or from routine core analysis data.

These imaginary examples have assumed a single fluid which is inert with respect to the porous medium. Such simplified conditions rarely exist. In an earlier paragraph, relative impermeability resulting from interfacial tension between immiscible fluids was considered. This is equally applicable whether dealing with a whole gas reservoir against a caprock or with the behavior of a small gas bubble within a rock

pore. In the latter case, the gas bubble is entrapped within the pore until a sufficient pressure differential exists across the aperture to overcome the interfacial tension and push the bubble through into the next pore. While the bubble is entrapped within a pore space, it obstructs the flow of liquid through the pore space just as if the pore were filled with a solid. If a large number of pores become so obstructed, the effective permeability of the rock may be significantly reduced. Since the strength of the interfacial tension is inversely proportional to the diameter of the aperture over which it exists, this blocking effect, the Jamin effect, becomes a problem as pore sizes are redueed. (In the author's opinion, many of the instances of effective permeability reduction in disposal wells may be attributed to the Jamin effect rather than to plugging of the apertures by solid precipitates. This is particularly true where reactions between injected fluid and host-rock or injected fluid and native fluid produce a gaseous reaction product.) It should be noted that any two immiscible fluids may result in Jamin obstruction, as for example oils emulsified in water.

A further factor in controlling permeability is the attraction between surface charges on the rock grains and the ionic or molecular composition of the transmitted fluid. Permeabilities to water, a polar liquid, may be lower than to kerosene which is non-polar. Similarly, the limited permeability of some argillaceous rocks is lower to brine than to fresh water due to attraction and retardation of the ionic solution by surface charges.

Relationships Between Permeability and Porosity

Since it is relatively easier to measure or estimate porosity than permeability, it is tempting to try to relate one to the other. Only under limited circumstances will this be reliable.

If a sand is of uniform grain size and the variable is degree of cementation, an approximate permeability/porosity relationship may be valid. On the other hand, decreasing grain size may reduce permeability without changing porosity. A fractured limestone may have a permeability of several thousand millidarcies with a porosity of only 2-3 percent, while a very finely divided dolomitic porosity may reach 20 percent without permeability exceeding 0.1 millidarcy.

Reservoir Rocks or Aquifers

The porous rock into which waste may be injected will generally be of two types, sandstones or carbonates.

Sandstones

Sandstones eonsist primarily of quartz grains and, when free of other materials and not heavily cemented, may be similar to the glass bead model deseribed above.

The quartz grains may be nearly spherieal or angular, well sorted, or poorly sorted, their size varying from two millimeters in diameter to a few thousandths of a millimeter. They may be bonded together primarily by frietion and intergrowth of the quartz or by the addition of silieeous material, earbonates or elay minerals. Their porosity and permeability may, under ideal eireumstanees, be almost homogeneous. However, the pattern and eharaeter of sandstone deposition is variable, ranging from extensive, well-sorted, thiek "blanket" sands to small lenses of a few inehes in thiekness and a few hundred square feet in area. Commonly, sands are interlaminated with shale or silt representing brief alterations of the depositional environment. Usually sueh laminations are horizontal or parallel to the bedding surfaee and laterally extensive. However, when these laminations oeeur on the steep slopes of a sandbar, or the front of a deltaie deposit, or within the ehannel of a surfaee or submarine stream, they may be deposited at steeply dipping angles. The areal extent of the sands may be eurtailed by truneation and overlap of subsequent depositional eyeles. In the former ease, lateral permeability may not be substantially redueed while in the latter ease permeability in all direetions may be affeeted in varying degrees. Thus, while the permeability and porosity development may be nearly isotropie within a small sample of a sandstone unit, these properties may be biased direetionally by seemingly minor variations in grain size and depositional pattern.

From the ehemieal point of view, quartz, the major eomponent of sandstones, is essentially inert with respeet to most liquids, ineluding most industrial wastes. However, the eementing material and other minerals mingled with the sand grains may be sensitive to ehemieal reaetion. Perhaps the most eommon extraneous eement in sandstones is ealeite, ealeium earbonate, whieh is readily soluble in weak aeid resulting in loosening and disassoeiation of the sand grains. Clay minerals are rare as a eement but they are eommonly found disseminated throughout the pore spaee within sandstone. As will be diseussed in detail later, some elay minerals may expand eonsiderably upon exposure to eertain liquids. This results in reduetion of effeetive pore spaee and may result in obstruetion in the permeable apertures. Without expansion of the elay minerals, loose flakes of elay may eolleet between grain apertures, elogging the aperture and redueing the perme-

ability. This "mobile particle" effect seems prevalent under high rates of flow which may strip the clay particles from the walls of pores and compact them into the intergranular apertures.

Carbonate Rocks

The carbonate rocks encountered in subsurface disposal consist of limestone, composed of calcium carbonate; dolomite, a carbonate in which calcium and magnesium occur in approximately equal proportion; or some intermediate lithology, a dolomitic limestone.

The porosity and permeability pattern within carbonates is more complex than that encountered in sandstone. However, a few carbonate rocks composed of fossil fragments or oölites (sperical accretions of carbonate) may provide the granular sort of pore net associated with sandstones. Commonly, carbonate porosity is of a secondary nature, having been induced by the dissolution of the carbonate by weakly acid waters permeating the formation or alteration of the chemical composition of the rock. Occasionally carbonate porosity results from the inclusion of porous fossils, such as coral, within the carbonate formation. These porosity-forming agents are inherently random in their occurrence and effect and produce complex reservoirs which are difficult to evaluate.

The Enclosure

The term *enclosure* is proposed to describe all the factors enabling a rock-fluid system to contain the injected fluid within an intended reservoir. The required limitations of flow may be imposed by the nature of the enclosing rock, by hydrologic conditions, or by a combination of both. Whereas such terms as "trap," "closure," and "caprock" all imply restraint primarily in the vertically upward sense, "enclosure" has no such directional limitations.

Rock Types Contributing to Enclosure

Any rock type, if dense, may serve as a caprock or aquiclude, even heavily cemented sandstones. However, the common lithologic permeability barriers are shales and dense carbonates.

Shales

Shales are composed primarily of thin flakes or aggregates of flakes of clay minerals bonded together by friction and by adhesion to thin

intervening layers of water. The clay minerals consist of exceedingly thin water layers sandwiched between silicate sheets a few molecules thick. If it is assumed that all the volume occupied by water is pore space, shales have a very high porosity, ranging from 10 percent to 40 percent.[1] However, most of this water is ionically bonded to the clay minerals and immobilized. The water may be considered as part of the rock itself. Excessive dehydration of shales or of the clay minerals results in decreasing strength and ultimately in total disintegration. Conversely, in the absence of a compressive load, many shales tend to absorb water by capillary action into the space between flakes or laminations, separating the components and reducing strength. It should be noted that the effective compressive stress exerted on shale, or any other rock, is the difference between the stress applied to the rock and the pressure of the internal fluids. An increase in the internal fluid pressure contributes to the weakening of a shale, just as does reduction in overburden pressure.

In some clay minerals, the montmorillonite group, the thickness of the intersilicate water layer is variable according to the exchangeable cation content of the internal water. The water layer may be a monomolecular film in the presence of an abundance of sodium, but it may be virtually infinite in thickness in cation-free water. The resulting changes in volume and in physical strength may be useful properties when the mineral is used in drilling muds or grouting materials. This ability to swell and reduce permeability may, under opportune conditions, contribute to the sealing of permeability barriers. On the other hand, lattice expansion reduces the strength of the rock of which the clay is a part, and may reduce permeability in rocks in which flow is desired as effectively as in those where low permeability is required.

The effectiveness of shale as an impermeable barrier to fluid movement lies primarily in two characteristics. The first is the fact that while the porosity and the water content are high, the water is immobilized within the very fine pores of the shale structure. The second factor lies in the mechanical behavior of shales which, due to their high water content and to the platy structure, behave as ductile or pseudo-plastic solids. When fractures, joints, and other discontinuities exist, the shale may extrude under the pressure of the overlaying rock load to fill any voids. In short, shale may be self-sealing.

[1] Paleozoic shales in Pennsylvania are commonly exceedingly dense and may be expected to fall in the lowest portion of this range.

Other Lithologic Barriers

The effectiveness of non-ductile rocks as flow barriers lies in their density (the absence of significant effective porosity or of permeable interconnection).

Non-ductile rocks are analogous to a glass jar and, while like glass are effective in preventing flow, are also subject to the same weakness, brittleness. While at high pressures the carbonates and other brittle, low permeability rocks may deform elastically, the sealing of natural vertical discontinuities is often dependent upon secondary mineralization, the deposition of minerals within the structural discontinuities.

The only impermeable sedimentary lithology of common occurrence is thickly bedded salt. Salt contains little primary porosity and has the property of ductile behavior at relatively low pressures. This property contributes both to the further reduction of intrinsic porosity and to the healing of fractures or similar physical discontinuities.

A sealing tendency may be supplied by "creep," the distortion and restructuring of crystals under stress, particularly in carbonates and salt. Of the three mechanisms available to brittle, low permeability rocks, only elastic deformation can seal newly induced fractures rapidly. The other mechanisms may take thousands of years.

Hydrologic Barriers

The capability of most reservoirs is partially controlled by conditions existing in the fluid portion of the rock-fluid system.

Hydrostatic entrapment through gravity segregation plays an important role in most oil and gas accumulations (Fig. 8A), the lighter hydrocarbons "floating" above the native brine within a superposed structural or stratigraphic trap. Dense liquids (relative to water) may be similarly contained at the bottom of a structural low.

If a flow is present in the reservoir (Fig. 8B), either naturally or artificially induced, lateral hydrodynamic forces are added to the gravitational effects and the location of conditions favoring entrapment may be shifted. (It will be noted that in effect the isopotential surface has been tilted.)

If no density contrast exists between indigenous and injected fluids, a counter flow of the native brine may prevent flow of the extraneous liquid "upstream."

These hydrologic controls on flow may be less effective if the native and extraneous liquids are miscible, the rates of diffusion then becoming a factor.

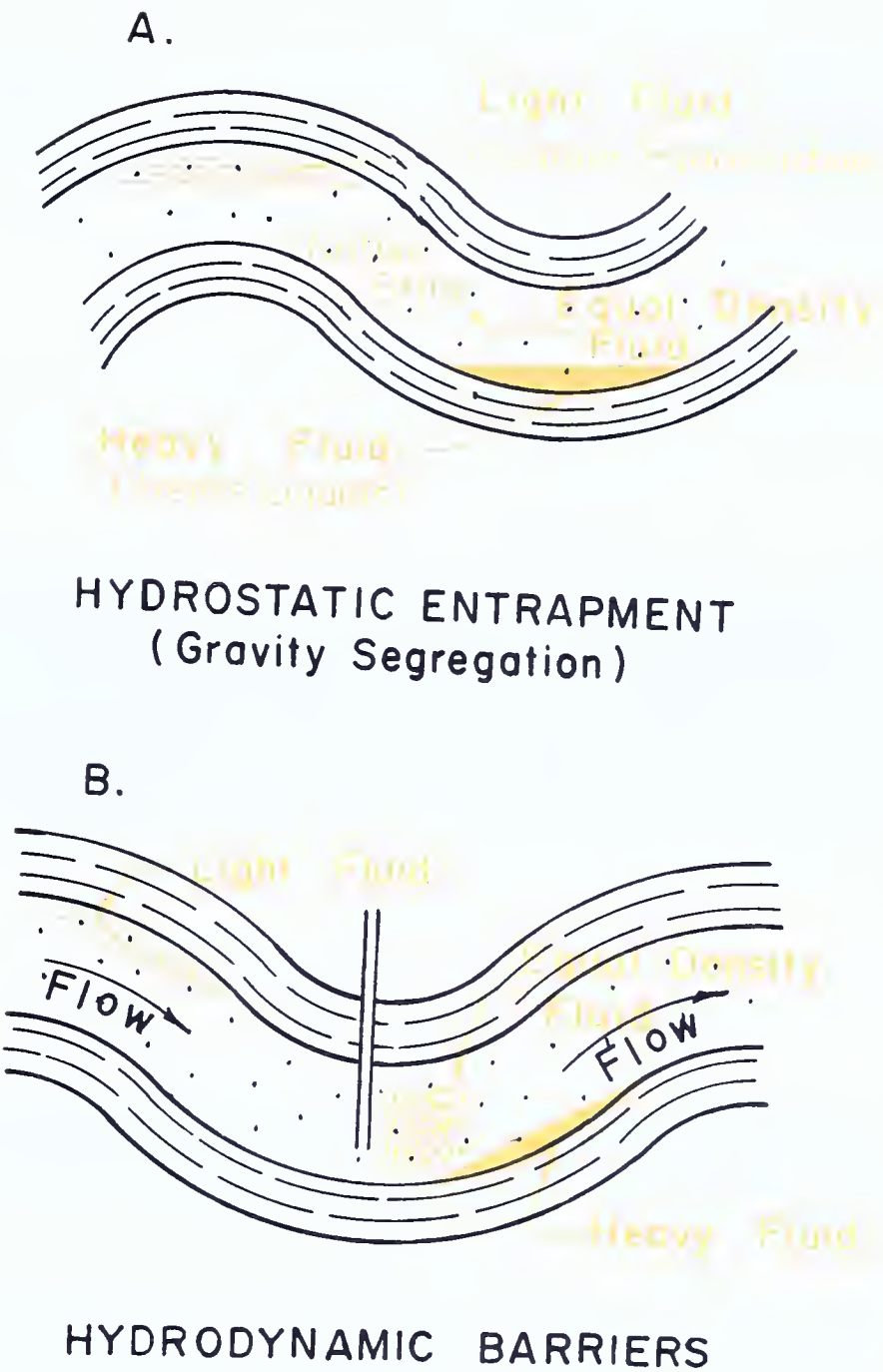


Figure 8. Hydrostatic and hydrodynamic flow barriers.

Finally, if the fluids are immiscible, the threshold pressure effect discussed in earlier paragraphs may be considered an additional hydrologic barrier.

THE EFFECTS OF FLUID INJECTION

If a fluid is to be injected into a reservoir which is already liquid filled, it must result in an increase in pressure and the injected fluid must be accommodated by one or more of the following mechanisms.

a. Expulsion of the native fluid.
b. Compression of either or both the native and the injected fluid.
c. Physical expansion of the rock pore space.

Effects of Pressure

The pressure must be raised at the point of injection if fluid movement is to be created.

Therefore, the first effect upon the subsurface environment is a local increase in fluid pressure. While increasing pressure differential increases input rate, there are some finite limits on the magnitude of the differential which can be accepted. Some limits are imposed by matters of the mechanical strength of the well's casing and some by the cementation of casing to the bore hole wall. Further limitations on input pressure are imposed by geological considerations.

Fracturing

If the pressure of the fluid within rock pores exceeds the stress on the grains, it may force the rock apart creating fractures (in a plane normal to the direction of least stress).

Most rocks have a low tensile strength and their compressive strength is primarily due to intergranular friction. Determination of the stress condition of deeply buried rock is a difficult problem. The overburden pressure applied by the weight of overlying rock may be estimated as approximately 1.2 pounds per square inch per foot of depth. If the densities of the overlying formations are known, the overburden pressure may be calculated accurately. One anticipates that the least stress direction will be in a horizontal plane. Rock below a few hundreds of feet of depth is often in a state of horizontal tension with a lateral stress component less than the overburden pressure, which may result in vertical fracturing.

The use of excessive pore pressure to create fractures is employed as a means of increasing the effective area through which fluids may be injected into or withdrawn from a formation.

In most instances the volume of injection and period of elevated pressure are small. The propogation of fractures may be halted upon encountering less brittle lithologies. Under these limited conditions of high pressure fracturing, oil field histories show many cases where fractures have accidentally been induced into higher or lower water-bearing formations.

The injection pressure of a waste disposal operation must be maintained at a level substantially below the overburden pressure to minimize the risk of creating artificial leaks by inadvertent fracturing and, perhaps more commonly, by extension of existing fractures, either of which may result in loss of control over the injection area.

If the "frac-pressure" in the vicinity of the well bore has been determined by stimulative fracture treatment, it is unwise to assume that the same frac-pressure will apply throughout the formation under conditions of prolonged injection.

Faulting

If fractures can be induced in coherent rock, fluid pressures of lower magnitude may open pre-existing planes of weakness such as joints, bedding-plane fractures and faults.

If shear stress already exists on a fault plane, the hydraulic "wedging" effect of elevated fluid pressure may be sufficient to initiate movement by reducing the friction between fault faces. Recent modest earthquake activity in the Denver, Colorado area has been attributed to a mechanism originating from disposal operations.

A conservative level of fluid pressures is clearly desirable, particularly when disposing of hazardous wastes.

It may be argued that the use of high injection pressures is commonplace in water flooding in the oil industry. On the other hand, it is recognized in the oil industry that these injected waters do not always go where they are intended. While this has had undesirable consequences, they are of less magnitude than would be incurred with a toxic waste injected in large volume over a prolonged period.

Pore Space Enlargement

An increase in fluid pressure lowers the compressive force on the rock matrix with resultant expansion of pore space.

Rock is slightly compressible, shrinking on the average three to five millionths of volume per pound per square inch pressure increase. While the numerical value of rock compressibility is small, the volume of rock affected is often large and a variation of fluid pressure of a few tens of pounds per square inch may alter reservoir volume.

Liquid Compressibility

The compressibility of water is approximately 3 millionths volume change per psi. As with rock compressibility, the volumetric effects of liquid compressibility may be substantial when applied to large reservoirs, despite its small numerical value.

As liquid is injected, it is restrained in its outward movement by the permeability of the surrounding rock and some of the liquid is temporarily accommodated by compressibility.

The liquid behaves as an elasticoviscous or Maxwell liquid, which is analogous to a spring coupled to a shock absorber (Fig. 9). The spring (compressibility) absorbs much of the initial motion but this motion is gradually imparted to the other end of the system at a rate controlled by the damping action of the shock absorber (permeability).

In a homogeneous reservoir both the pressure and rate of fluid advance drop rapidly outward from the well bore due to radial flow as well as to the effects of compressibility.

The magnitude of the compressibility (spring) effect is largely dependent upon the volume of fluid present or the porosity, while the damping effect is controlled by the level of permeability present.

The transmission of fluid through a low porosity, high permeability zone, such as a fractured limestone, may be rapid, while transmission through a high porosity, low permeability formation, as a shaly sand, may be retarded.

When injection or withdrawal operations are discontinuous, the variation of flow rates and compressibility in the reservoir and enclosing rock may result in complex patterns of flow and emplacement of injected material.

Effects of Displacement

Injection creates an area of high potential with relation to the existing reservoir, and, through time, the reservoir must return to a condition of

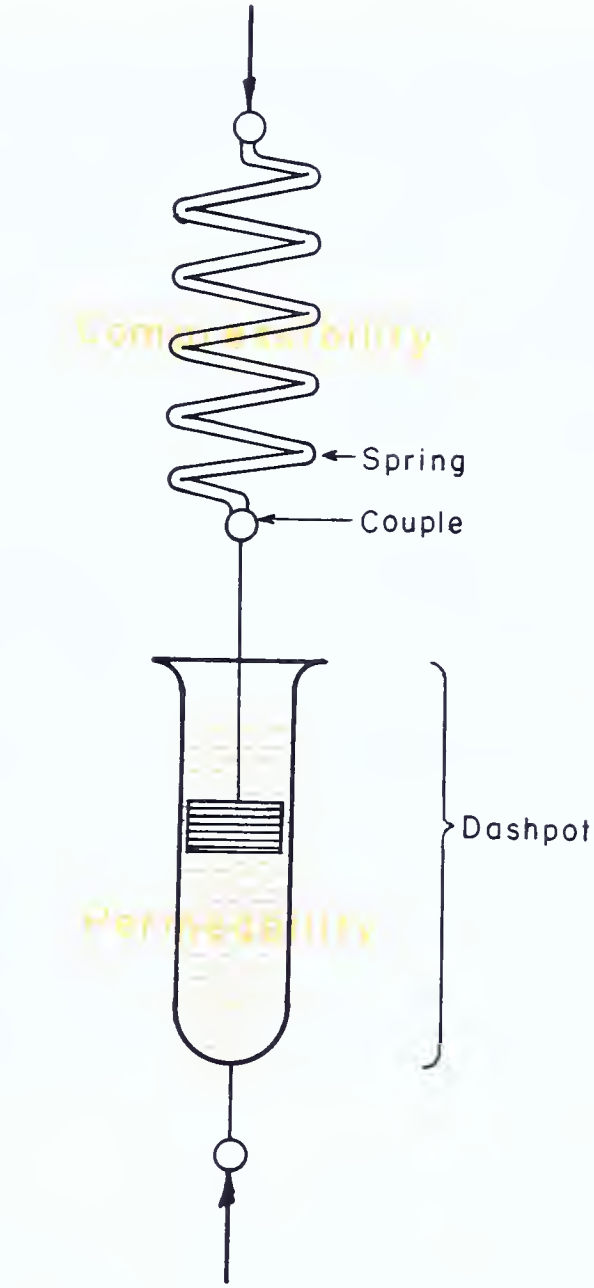


Figure 9. The elements of a Maxwell liquid.

pressure equilibrium by displacement of the fluid from within the high pressure region. The inevitability of dissipation of the injected fluid as well as the local pressure increase should be recognized.

Under ideal conditions the amount of injected fluid which can be accommodated within a reservoir is high and the radius of effect low. It has been shown that an aquifer of fifty-foot thickness and 20 percent porosity, into which fluid is injected at 100 gallons per minute, after 50 years will contain the effluent within a radius of ½ mile. It should be noted, however, that this is a transient situation and presumes ideal conditions.

A pressure differential is necessary to cause the displacement of effluent into the reservoir. This differential will, in most instances, initiate flow into the confining lithologic units, the caprock or aquiclude. Most so-called impermeable formations have measured permeability of the order of 10^{-5} to 10^{-8} millidarcies. While the "thruput" in such a formation may appear small, it must be remembered that the effective areas involved in disposal include tens or hundreds of acres at a minimum. A fifty-foot thick formation with a vertical permeability of 10^{-8} millidarcies will transmit approximately 50 gallons of water per day per acre of area at 100 psi pressure differential.

Further, any internal variation in permeability, either a directional bias or a high permeability zone, will distort the fluid flow pattern (Fig. 10). Uniform permeability distribution throughout the full thickness of reservoir rocks is rare. Even excluding consideration of bedding planes and other fractures, it is not unusual to have horizontal zones within a reservoir which exeeed the average permeability by a factor of ten. Experience in oil and gas production, particularly water flooding, and in aquifer gas storage confirms the rarity of obtaining a uniform radial-flow pattern.

It is important that permeability arising from fractures and solution channels be recognized in addition to intergranular permeability. While particularly prevalent in the denser, soluble carbonate rocks, fractures and solution channels are possible in almost all lithologies. The transmissibility of fractures and solution channels may equal or exceed that of the intrinsic system. By their nature they are directional both vertically and laterally. These fractures and solution channels may conduct the injected fluid rapidly and in large volume to a wholly different location than that originally anticipated.

Volumetric calculations of the displacement of injected liquids should include consideration of effects of bypassed "blind" pore space and the mingling of injected waste with native fluid. The latter increases the effective volume of the effluent, although diluting its concentration.

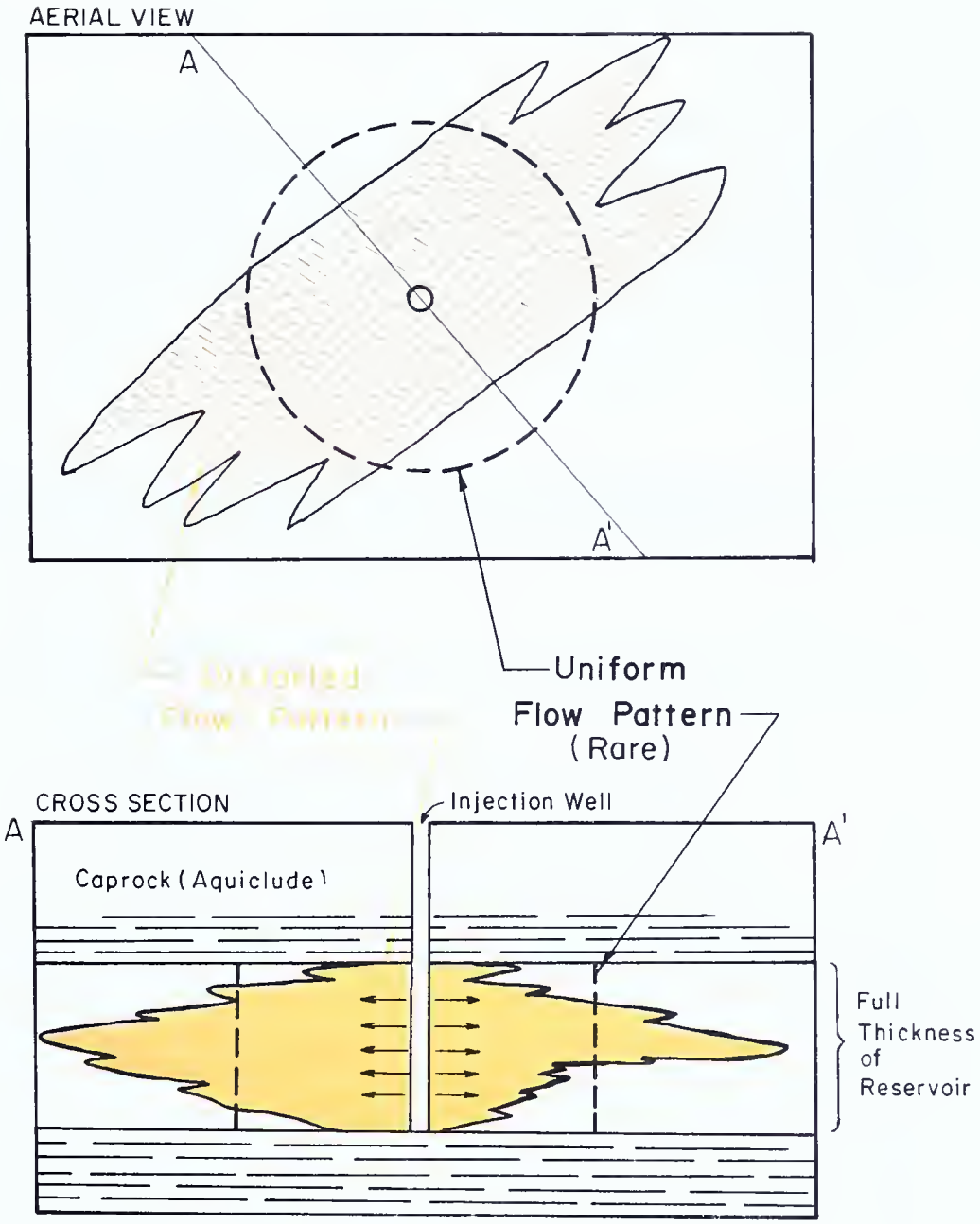


Figure 10. Anisotropic flow patterns.

Extended Effects

The area of effect of an injection operation is considered to be defined by the extent of the effluent in its reservoir. While this area may be difficult to define, the area of pressure effect is even greater and more difficult to predict.

The periodic operation of a water-supply well at a cannery is detectable in a gas storage field almost ten miles away. Water-flooding injection in one pool is reflected in pressure responses in another pool twelve miles distant within a few days. Salt water from ruptured casing in an oil well is detected in a water well two miles away within two months.

Oil field and ground-water experience shows too many examples of far-ranging and unpredictable displacement and pressure responses to justify confidence in simplistic calculations based upon idealized conditions.

SUMMARY

It cannot be overstressed that the introduction of waste liquids into the subsurface is a permanent alteration of the subsurface environment.

The magnitude of these changes may be small, but they are cumulative. For this reason, attention must be given to the density of disposal projects and to the cumulative volumes injected. Just as raw sewage from one town may not pollute a large lake or river, one disposal project may not cause undesirable changes in the subsurface. However, the cumulative effects of large scale disposal of raw sewage can be disastrous, as would be unrestricted subsurface disposal of large volumes of waste by many projects within an area.

Most subsurface liquids are heavily saturated solutions of sodium chloride and other salts. These subsurface brines are undesirable if displaced into the near-surface environment. Many aquifers charged with fresh water at the surface are brine-filled where deeply buried. The long-term injection of large volumes of waste must eventually result in the upward displacement of the brine intraformationally or through fractures into the fresh-water zone. The concentration of subsurface brines is so great, up to the order of 300,000 parts per million, that the intermixing of even one gallon will render several thousands of gallons of fresh water unfit for human use.

Clearly it is important to discriminate between "disposal" and "storage." True disposal and isolation of an effluent for a prolonged period of time may be difficult to accomplish. Storage for a finite period of time may be accomplished by compressibility and by the slow rate of

dispersal at increasing distances from the injection site. In either case, it will be seen that it is difficult to predict where an injected liquid will be at any given point of time. Yet, prudence demands that such predictions be made and confirmed.

Subsurface liquid waste disposal is a useful concept of considerable potential benefit to society. It is, however, an endeavor requiring careful planning and foresight, together with careful operation and observation, to prevent ultimate environmental damage which outweighs the immediate benefit. The planners of subsurface disposal projects must think in terms of the whole rock-fluid system, in terms of tectonism, regional stratigraphic relationships, structural discontinuities and stresses, hydrodynamics, and interractive chemistry between all components of the systems, not just in terms of the immediate problems of fluid flow and storage in the vicinity of the injection site.

PART II — IMPLEMENTATION: GUIDELINES AND TECHNIQUES

The fundamental requirements for subsurface liquid waste disposal are:

1. The effluents must be removed from our immediate environment for as long as they retain the ability to create a hazard or nuisance.
2. The injected wastes must neither contaminate our surface or subsurface resources nor reduce their accessibility.
3. The process of disposal must not result in damage to the surface environment either directly or by secondary effects.

Some corollaries are equally apparent. Once the complexity of the subsurface rock/fluid system has been recognized, it becomes obvious that subsurface waste disposal must be a closely controlled operation. We cannot rely upon broad generalizations regarding injected fluid behavior as an adequate background for the design and operation of such projects. We must seek a "custom fit" between the requirements of industry and the specific geological conditions prevailing in the area of effect.

Since our abilities to acquire and interpret such specific knowledge are limited, deviations from predicted performance must be anticipated. Accordingly, we must be able to recognize such deviations and take corrective action when required. *Adequate design, therefore, must include provision for monitoring of performance and remedial action, even abandonment.*

For the duration of the potentially harmful life of the injected waste, we must seek to be able to predict, monitor, and control the effluent, *what it is, where it is,* and *what it is doing.* Unless this can be done with a high degree of reliability, we are in effect simply "dumping" our wastes. These conditions are rigorous and costly, but where they cannot be met it may be that waste liquid injection is not the appropriate answer to our disposal problems. The "hidden" costs of uncontrolled dumping in the subsurface may be infinitely higher, not only to society, but directly to the using industries themselves through loss of investment as well as liability for damages (Appendix A).

THE PRELIMINARY INVESTIGATION

The preliminary investigation includes two stages:

1. Definition of the character of the disposal problem.
2. Definition of the geological requirements imposed by this problem.

Is it possible that a suitable geological site exists adequate to meet the specific industrial need? Does the probability of finding a suitable geological situation justify the costs and risks of exploration? What are the critical factors which must be carefully confirmed?

Clearly, a full understanding of the nature of the effluent, requirements of the processes, and economics of the using industry are a prerequisite to exploration for a suitable subsurface waste disposal site. Many decisions regarding the feasibility of subsurface liquid waste disposal are matters of relative judgement. We know that we will upset the subsurface environment, at least in minor degree. We must recognize the ever present chance that this will have some unforeseen effect upon the surface and shallow subsurface. Thus, before we undertake the more difficult and expensive tasks of active exploration, it is well to establish a framework for decision based upon the readily available information.

The elements of the preliminary investigation are outlined in some detail on the following pages. Suggested sources for the requisite data are also included. Since it is unlikely that comprehensive and conclusive information on all aspects can be acquired during the preliminary investigation, certain requirements have been categorized as "essential," "highly desirable," and "useful."

Neither the list of factors to be considered nor the categorization of their importance should be taken as absolute. The interrelationship of human, environmental, and geological factors is too complex. There can be no substitute for imaginative and diligent consideration of all

the effects and consequences of each individual disposal project. *The following outline and accompanying remarks are intended only as a starting point to assist in the orderly assembly and evaluation of the information upon which a disposal project may be designed.*

The Two Concepts of Subsurface Waste Disposal

There are two concepts of subsurface waste disposal, each appropriate for specific kinds of effluent and each having specific geological requirements (Fig. 11 and Table 1).

Table 1. *Preliminary Investigation Defining the Industrial Problem*

INFORMATION REQUIRED	SOURCES	REMARKS
I. What is the nature of the material to be injected?		
A. Its harmful characteristics		
1. What are its undesirable characteristics?		
a. Primary? (e.g. acid liquors)		
b. Secondary? (e.g. minor content of cyanides)		
2. Are these characteristics subject to attenuation or neutralization?	Chemical (and Biological) Analysis: Experimentation; Public Health Services	Complete understanding of *all* potential dangerous components in the effluent is *essential.*
a. Under what conditions? (e.g. reactions with carbonate)		
b. At what levels of concentration do they become safe?		
3. What type and degree of hazard does the effluent present?		
a. Direct danger to human life and health?		
b. Pollution of air or water?		
c. "Lesser" hazards?		

Table 1. *(Continued)*

INFORMATION REQUIRED	SOURCES	REMARKS
B. Its chemical and physical characteristics		
1. Is the waste reactive?		
a. Acid or basic?		
b. With rock minerals or fluids?		Reaction products may be more dangerous than original effluent.
c. What reaction products? Precipitates, gasses?		
d. What is the pollution potential and character of the reaction products?		
2. What is its physical state?	Chemical and Physical Analysis.	Essential for adequate planning.
a. Liquid solution?		
b. Suspended solids?		
c. Emulsion?		
d. Entrained gasses?		
3. What are its physical properties?		
a. Viscosity? (including consideration of effect of suspensions and emulsions)		
b. Miscibility?		
c. Compressibility?		
d. Specific Gravity?		
4. Is it susceptible to partial treatment before injection?		
a. Filtration?	Experimentation and pilot testing.	
b. Cooling?		
c. Concentration		
d. Chemical Alteration?		
II. What are the operational and economic factors?		
A. Volume and rate requirements	Industrial Engineering Staff.	Essential for planning.
1. What volume must be injected?		
2. At what rate?		
3. For how long?		
4. Must injection be continuous or periodic?		

Table 1. *(Continued)*

INFORMATION REQUIRED	SOURCES	REMARKS
5. Can interruptions be tolerated? 6. How far can effluent be transported to disposal site?	Industrial Engineering Staff.	Essential for planning.
B. Economic Factors 1. Maximum acceptable cost for total project? 2. Maximum acceptable cost for exploration and evaluation? 3. Acceptable level of risk of functional failure? 4. Acceptable level of environmental risk (liability)?	Management.	Useful for planning; essential before development.
III. What are the environmental considerations? A. Human Factors? 1. What is the population distribution within the proposed disposal area? 2. What and where will be the future population growth? 3. What are the "sensitive" environmental factors upon which the population depends? a. Water? b. Agriculture and forestry? c. Mineral resources? d. Soil and rock stability?	Local, State and Federal Government Agencies, Planning Commissions.	Essential.
4. In what ways could the injection of wastes affect the environment?	Scientific evaluation by Company Staff; Consultants; Public Agencies.	Essential.
B. Economic Factors — Other Minerals 1. Other mineral values in the area? 2. Can disposal damage or limit access to other minerals?	Geological Studies.	Desirable; essential before development.

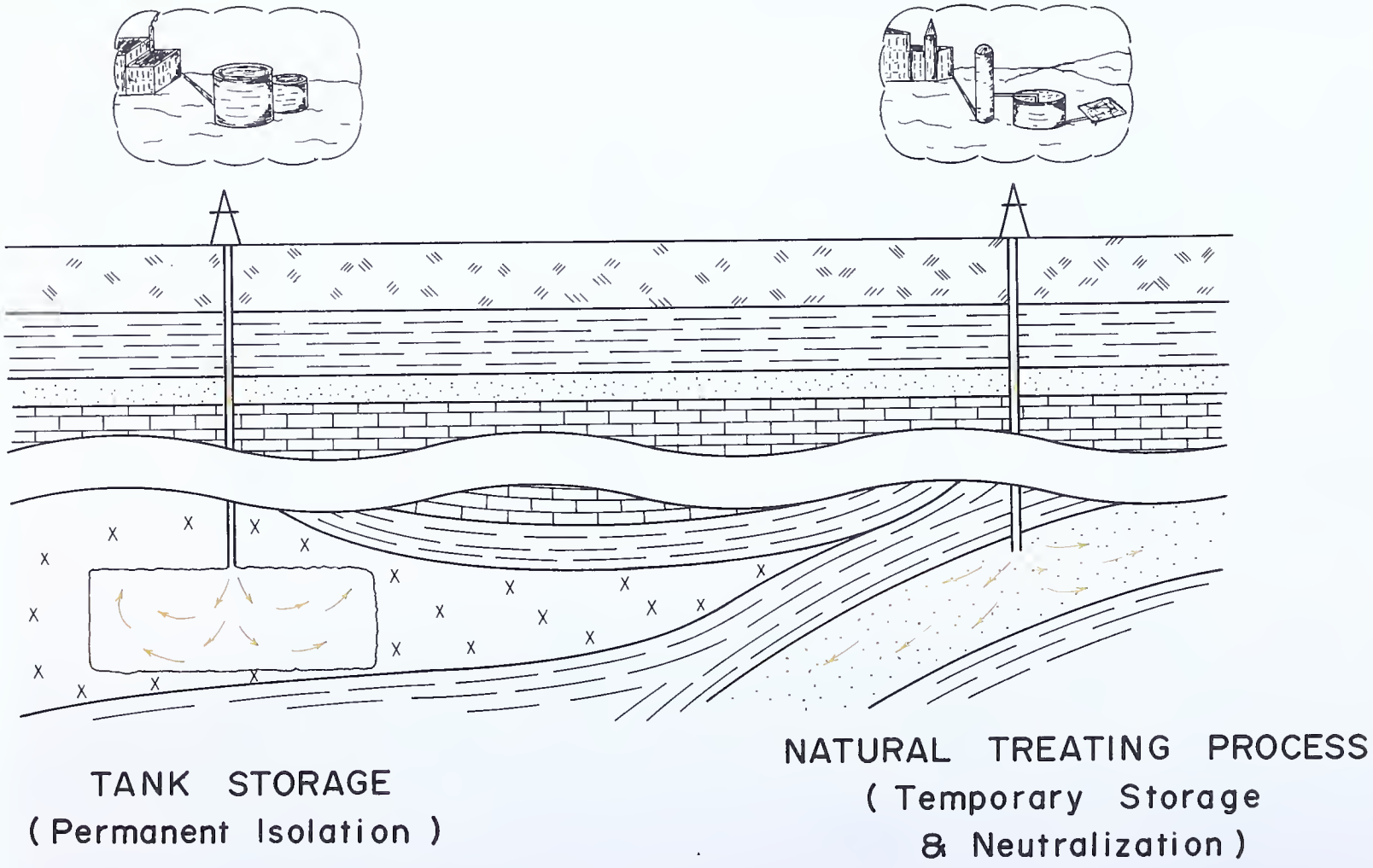


Figure 11. Two concepts of subsurface waste disposal.

The Subsurface "Tank"

The prevailing public impression of subsurface waste disposal conceives of a wholly impermeable subsurface "tank" in which effluent is permanently isolated. Disposal sites of this nature are entirely possible but in practice they are rarely used because of the limited occurrence of the very special geological conditions required.

"Tank" type storage of effluents may be developed in salt caverns or in isolated sand lenses which have been partially dewatered. In either case only modest quantities of effluent can be contained.

Stable, concentrated, highly toxic liquids may effectively be disposed of in subsurface "tanks" when the enclosure is well established.

Temporary Storage and Neutralization

More commonly, subsurface waste disposal facilities take a form of a natural treating process in which the effluent is stored within the rock while its undesirable aspects are diminished by chemical reaction, by filtration, by radioactive decay, or by dilution. The holding time may extend to tens of thousands of years but eventually the injected liquids are returned to the normal hydrologic cycle.

The natural treating process concept of subsurface waste disposal is not unlike septic tank disposal of human wastes and is subject to many of the same limitations. It is effective only for degradable pollutants and only when the holding time of the system is adequate to accomplish complete removal of harmful characteristics. It is clearly necessary to include a realistic appraisal of the holding time of such a system in the evaluation of a disposal project.

Nondegradable materials should not be disposed of in the more common natural treating process form of disposal operation. Reliance upon difusion and dilution as a means of diminishment is acceptable only when there is an opportunity to control the volume of fluid injected relative to the volume of the rock/fluid system.

The raw-sewage output of one dwelling unit may not significantly pollute a stream but the situation worsens rapidly with increasing population density. We may confidently expect that the same will be true with regard to subsurface waters. In future years we may have cause for concern for the rates and volumes of effluent injected underground.

The distinction between "tank" storage (permanent isolation) and the natural treating process (temporary storage and neutralization) is crucial (Table 2).

Table 2. *Preliminary Investigation Defining the Geological Requirements*

INFORMATION REQUIRED	SOURCES	REMARKS
I. What type of disposal is required?		
A. Permanent Isolation		
1. Stable toxic or hazardous components in effluent?		
2. Extensive development of subsurface — mining, etc.?		
3. Uncertain continuity of reservoirs or caprock over extensive area?		
B. Temporary Storage (Pending Alteration)		
1. Neutralized by chemical reaction?		
2. Neutralized by time? (radioactive decay)		
3. Attenuated by dilution? (limited instances only)		
II. What type of enclosure is required?	Consideration of industrial requirements and character of effluent.	Essential.
A. For permanent isolation (the "tank" concept)		
1. Zero flow boundaries?		
a. Absolute impermeability?		
b. Hydrodynamic boundaries?		
2. In all directions?		
a. Vertical controls?		
b. Lateral controls?		
3. At all times?		
a. Alteration of geological environment?		
B. For temporary storage (the "natural treating process" concept)		
1. Adequate constraints on fluid flow?		
a. Lithologic?		
b. Hydrodynamic?		
2. In critical directions?		

Table 2. *(Continued)*

INFORMATION REQUIRED	SOURCES	REMARKS
a. Between effluent and surface?		
b. Between effluent and subsurface resources?		
c. Of sufficient extent to ensure neutralization of effluent before escape?		
3. Until no harmful characteristics remain?		
a. Under existing geological conditions?		
b. Under such altered geological conditions as may be reasonably anticipated?		
III. What characteristics of the reservoir are required?		
A. Capacity	Consideration of industrial requirements and character of effluent.	Essential.
1. Ultimate capacity = 1 unit volume of effluent per million volumes of water-filled *effective* pore space per psi pressure increase?		
2. Working capacity determined by?		
a. Permeability?		
b. Permeability profile?		
c. Pressure limits?		
d. Time in transit if temporary storage?		
B. Injectivity		
1. Primary factors?		
a. Required disposal rate?		
b. Permeability?		
c. Pressure limits?		
d. Thickness of section?		

Table 2. *(Continued)*

INFORMATION REQUIRED	SOURCES	REMARKS
2. Other considerations? a. Susceptibility of reservoir to plugging? b. Permeability profile, bypass?	Consideration of industrial requirements and character of effluent.	Essential.
C. Criteria for pressure* limits 1. Overburden pressure? (rock pressure) a. 75% suggested maximum? (at 1.2 psi/foot of depth) b. Consider also least stress orientation? 2. Hydrostatic pressure? a. 110% suggested maximum initially, possible 120%. b. Consider also mechanical effects of increased pore pressure?	Not determinable at this stage; however, recognition of limits will be required in evaluation of exploratory results.	Useful at this stage. Essential before injection.
D. Chemical Requirements 1. Is a reaction with rock minerals an essential part of the project? a. What minerals? b. How much? 2. Could a reaction with rock minerals have a damaging effect upon the project? a. What minerals? b. What quantity?	Chemical investigations by using industry.	Useful at this stage. Essential before injection.

* All pressures referred to are bottom-hole pressures. The pressure at the bottom of the hole is the observed surface or well-head pressure *plus* the pressure of any fluid column existing within the well.

When the preliminary investigation phase has been completed, we should have a specific shopping list to guide us during the exploratory phase. Most of the information used in making up our shopping list

should be readily available to the industry proposing the disposal facility. Evaluation of the human environment and the resources necessary to support it should not be difficult in view of the assistance available through local, state and federal governmental agencies. The geological aspects of the shopping list are straightforward. They represent a projection of the industrial and environmental requirements to define the types of geologic situation which would be conducive to an efficient and safe disposal facility.

Limitations on Pressure

The question of acceptable pressure limits is not susceptible to precise definition, particularly during the preliminary exploration phase. Limits must be established not only for the local and transient pressures near the injection well but also for the ultimate, widespread equilibrium pressure. It is nevertheless necessary to make some working assumptions.

The conservative solution is to maintain pressures at or below those of the surrounding hydrological environment. At the other extreme, it might be possible to employ pressures approximating the lithostatic or overburden pressure. *From the point of safety, it is clearly desirable to minimize pressures since the existence of a positive pressure differential creates the potential for outward flow.* Efficient operations require the use of the highest possible pressures for injection to secure the highest input from the minimum number of wells or smallest completion zone and also for final equilibrium pressure to accommodate the largest amount of waste in the smallest amount of space.

In consideration of pressure limits, as in most other aspects of subsurface disposal, we must recognize the limitations of our knowledge and provide substantial safety factors.

What appears to be a massive salt deposit may still include a coarse sediment zone or some other potential conduit for leakage. Further, just as high pressures mean maximum rate of injection and maximum storage capacity, they also mean maximum rate of escape and carry with them the potential for maximum damage. In the absence of a direct pressure test on a proposed disposal reservoir, suggested pressure limits must be somewhat arbitrary. They should be used with caution. Any increase in the fluid pressure of the subsurface should be done slowly and with careful observation.

In the case of a "tank" type disposal facility, such as a salt cavity, where the enclosing rock is absolutely impermeable, *it is suggested that pressures should not exceed 75 percent of the lithostatic or over-*

burden pressure. The 25 percent margin of safety should provide a reasonable sealing pressure (lithostatic pressure less internal fluid pressure) to maintain impermeability (even in the presence of minor joints and fractures). In the event that the reservoir should be breached by some geological accident, the flow of fluids below this pressure should be restrained or retarded by overlying formations.

In the "temporary storage" type of disposal facility, the maximum allowable pressures must be determined in connection with the desired "holding time." Normally, such a disposal site will be in a laterally extensive, permeable formation sandwiched between formations of low permeability. The pressures must be low enough so that the effluent does not escape the system, either laterally through the permeable formation or vertically through the low permeability formations, before it is fully neutralized. Thus, determination of operating pressure depends heavily upon the evaluation of permeability in the enclosing formations as well as the reservoir itself. Unanticipated avenues of fluid migration are a very real possibility. For this reason, *it is suggested that initially pressures* should be so limited that the pressures against the enclosure, the interface with the confining lithology, *do not exceed 110 percent of the hydrostatic pressure in the surrounding fluid system.* Only after thorough and prolonged observation should higher pressures be used.

Determination of Pressure from Hydraulic Fracturing

It is exceedingly difficult to determine the *in situ* stress state and mechanical strength of deeply buried rock. There is however one source of data which can aid in establishing the absolute maximum pressure.

When a formation is hydraulically fractured to improve its productivity or injectivity the pressure is normally observed continuously throughout the course of the treatment. When the treatment is discontinued with an abrupt cessation of pumping, the fluid pressure drops sharply representing the loss of injection pressure. The pressure then declines gradually as the fluid phase attains equilibrium within the formation. The "instantaneous shut-in pressure" observed during a brief point in time when pump pressure has been removed but before the injected fluids have been bled off, is generally accepted as representing the minimum pressure needed to sustain or propagate an open fracture. Since it is unwise to artificially develop extensive fractures in a waste disposal well, it is evident that pressures equivalent to the "instantaneous shut-in pressure" must be avoided. Because of the in-

homogeneities in rock and the possibility that the "instantaneous shut-in pressure" in the immediate vicinity of the well-bore is not representative of the formation as a whole, it is desirable to limit the maximum pressure at any stage of the injection process to a pressure significantly below this critical point. A maximum pressure of 75 to 80 percent of "instantaneous shut-in" is suggested as an arbitrary maximum.

Monitoring and Control

We have said that it is necessary to be able to "predict, monitor, and control the effluent." A preliminary investigation should therefore include consideration of the requirements for monitoring and control as well as collection of the data necessary to predict performance.

Monitoring

Monitoring is an essential requirement for responsible subsurface disposal operations. Even if all possible information is gathered from pre-existing geological studies, from exploratory and development wells, and from disposal injection records themselves, we may acquire only a partial understanding of the complex rock/fluid system in the subsurface. It is advisable to expect the unexpected. Exploration for an evaluation of observation zones should be equally important to the exploration and evaluation of reservoir and enclosure.

There are two possible approaches to monitoring:

1. The simplest is designed to determine whether or not the project is working as expected. It is a "go no-go" test. It presumes that the disposal operator will cease injection immediately upon unfavorable indication in the monitoring system; undertake without delay to commence withdrawal; and will take other measures which may be indicated to protect the surface and subsurface environments.
2. The alternative approach is one which will enable the detection of the nature of the defect. This approach will permit the application of selective remedial measures.

The two approaches differ mainly in degree. The techniques are not notably dissimilar; but must be designed to meet the specific geological conditions surrounding the project.

The types of monitoring may be identified as "internal" and "external." *Internal monitoring* is performed much as one might seek to test the soundness of a steel tank. That is to say, provision is made *to monitor the internal pressure when the contents* of the tank *are shut-in. Any*

indication of pressure loss indicates a defect. This type of monitoring is neither very sensitive nor very definitive when applied to waste disposal. It requires prolonged periods of shut-in to allow internal pressures to approach equilibrium and fails to give any indication of the location of leakage.

External monitoring involves the observation of fluid pressures and/or contents *in formations surrounding the reservoir.* Perhaps the simplest external monitoring system might be developed for disposal in a sand lens wholly enclosed by shales. Two wells (or a single well with a multiple completion) opened into the next overlying and underlying permeable formations should permit the recognition of fluid loss from the reservoir. This fluid loss will show either by increased static water levels (increased pressure) in either of these formations or by the appearance of traces of the effluent.

Where there is a possibility of lateral movement, additional observation wells may be required around the perimeter of the project. The number and position of observation wells will depend upon the fluid transmitting characteristics of adjacent formations. Formations of low permeability will require more sensing points per unit area than those of high permeability. In the selection of observation horizons, care must be taken to be sure that they are ones of widespread continuity as well as of sufficient internal permeability.

Evaluation of feasibility of monitoring becomes an important part in the evaluation of the feasibility of the whole disposal project, particularly from the economic viewpoint (Fig. 12).

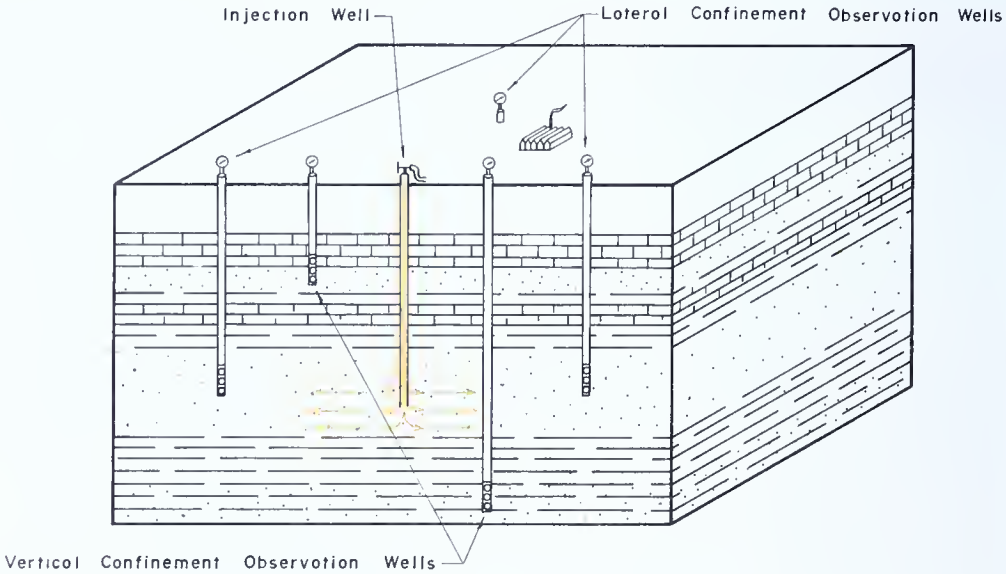


Figure 12. Schematic diagram of complete monitoring.

In geologic sections with few permeable formations, the selection of adequate observation zones close to the reservoir may present a severe problem. Inability to secure adequate monitoring should be considered a severe negative factor in the evaluation of any disposal project. For example, the absence of an adequate monitoring zone between a disposal horizon and a widely used freshwater aquifer would virtually condemn a disposal project.

Control

The effectiveness of a monitoring system is of academic interest unless there is a means of control. Usually the identification of observation zones and the preliminary design of monitoring systems will provide means of corrective control.

Control should be given careful consideration during the preliminary investigation phase. If, after a substantial volume of effluent has been injected, it becomes evident that it is not being retained in the desired reservoir, the questions must be asked, "how?" and "how quickly can it be brought under control?"

The injection well can be converted to withdrawal, resulting in both the lowering of pressure and reduction of volume of the effluent remaining within the subsurface. Possibly the observation zones may be temporarily pressurized in an effort to reverse flow, forcing the effluent back through the leaks from which it escaped. Alternatively, the observation zones may be used as buffer zones and pumped to remove the effluent which has escaped from the intended reservoir.

The objectives and requirements for monitoring and control should be clearly defined and carefully evaluated during the exploration and development phase.

EXPLORATION AND DEVELOPMENT

In practice, there will rarely be a clear-cut distinction between the *preliminary investigation* and *exploration–development* phases, for it is unlikely that deep well disposal would even be considered without some knowledge of the subsurface geologic section. By this time, we should have a rather definite idea of what we want in terms of volume of pore space, enclosing stratigraphic elements, monitoring and control zones, mineral and water composition, cost, and area of exploration.

The problem now is to find a suitable suite of geological conditions to meet these requirements. The gathering of data and its evaluation

ranges from initial library research of previously published geological information to the abandonment of the disposal project. In view of the limitations inherent in dealing with the unknown subsurface, we can afford to miss no opportunity to expand our knowledge of the lithologic, fluid, mechanical, and structural relationships involved in the project area. It is for this reason that exploration and development are treated as a single phase. Even the drilling of the last monitoring well should be regarded as an exploratory venture as well as a functional necessity.

The end point and goal of this phase is the "go ahead" decision, the point at which all practical sources of information have been exhausted and the data evaluated to determine whether the project should go into a full "on-stream" operation or should be abandoned.

The exploration and development phase can be broken down into three stages: 1) pre-drilling exploration, 2) drilling and testing, and 3) post-drilling evaluation. Professional geological assistance is particularly important during these stages to insure that a maximum of information is obtained.

It is not sufficient simply to identify formations, measure porosities and permeabilities, and observe fluid pressures. Trained geologists can relate seemingly minor clues to reveal more of the complex rock/fluid system, obtaining more knowledge per exploration dollar and often preventing costly failures.

Among unsuccessful subsurface disposal projects, the lack of adequate geological investigation and supervision has been a major contributing cause. Some projects were doomed from the outset because of a hostile geological environment and others have been costly failures due to incorrect interpretation of the geologic evidence.

Supplementary Exploration Techniques

There are several exploration techniques which may be employed to relieve certain ambiguities which may appear in the pre-drilling study (Table 3).

Seismic Exploration

If the preliminary investigation reveals that pertinent structural data is lacking, some seismic exploration may be justified.

Structural contouring may reveal a linear area of extremely steep dip. Such a feature may be interpreted either as a fault or as a simple

Table 3. *Pre-Drilling Exploration*

INFORMATION REQUIRED	SOURCES	REMARKS
I. General geological environment		
A. Stratigraphic section		
1. Potential disposal reservoirs		
a. Evidence of porosity and permeability	Published geologic literature, well records and other unpublished geologic material.	Essential.
b. Lithology		
c. Stratigraphic continuity, lensatic, blanket, channel fill, etc.		
d. Approximate thickness		
e. Approximate depth		
f. Contained fluids (volume and quality)		
2. Potential enclosure		
a. Evidence of low permeability		
b. Lithology		
c. Stratigraphic continuity		
d. Depth and location with relation to reservoir		
e. Approximate thickness		
B. Structural geology		
1. Existing features		
a. Location of major structural features, folds and faults	Published geologic literature; well records; useful information also found in ground-water quality and hydrodynamic studies.	Essential.
b. Joint and fracture patterns		
c. Igneous intrusives and metamorphic structure		
2. Potential structural changes		
a. Seismic history		
b. Volcanic history		

Table 3 *(Continued)*

INFORMATION REQUIRED	SOURCES	REMARKS
II. Subsurface Resources		
A. Ground Water		
1. Potable water		
a. Aquifers, recharge and discharge areas		
b. Water quality		
c. Capacity	Published geologic literature; well records; sanitary water boards, water surveys; field investigations.	Essential.
d. Pressure relationships and trends		
2. Other Waters		
a. Aquifers		
b. Quality		
c. Hydropotential data, depths, and pressures		
d. Permeability or capacity		
e. Evidence of intercommunication		
B. Other subsurface resources		
1. Oil and Gas		
a. Location relative to disposal site — geographic and stratigraphic		
b. Productive status —primary production, secondary, abandoned		
c. Productive mechanism — gas expansion, water drive, combination	Operating companies; geological surveys.	Essential.
d. Potential disposal site		
e. Potential monitoring or buffer zone		
f. Source of applicable reservoir data porosity, permeability		
g. Susceptible to damage or improvement by adjacent disposal operations		

Table 3 *(Continued)*

INFORMATION REQUIRED	SOURCES	REMARKS
h. Completion and plugging methods —possible leakage due to mechanical failures	Operating companies; geological surveys.	Essential.
2. Ores and solid fuels a. Location relative to disposal site — geographic and stratigraphic b. Productive status — undeveloped, operative, abandoned c. Susceptible to damage by adjacent disposal operations d. Source of potential damage to disposal operations	Operating companies; geological surveys; regulatory agencies, State and Federal.	Essential.
III. Re-evaluation A. Is there a reasonable possibility that an adequate reservoir or reservoirs are present in the geologic section?		As the above data are being assembled, the impact of the data upon the overall project should be constantly re-evaluated.
B. Is there a reasonable possibility of enclosure? Lithologic or hydrodynamic?		
C. Are there structural factors that may decrease the ultimate containment of the effluent under certain conditions?	Operating companies; geological surveys; regulatory agencies, State and Federal.	Essential.
D. Is there a reasonable possibility that adequate observation and buffer zones are present?		
E. What are the risks of interference with the recovery of other resources or interference with disposal by the recovery of other resources?		

Table 3 *(Continued)*

INFORMATION REQUIRED	SOURCES	REMARKS
F. Are the prospects of success sufficiently good to justify substantial future expense?	Operating companies; geological surveys; regulatory agencies, State and Federal.	Essential.
G. What aspects require further investigation and calculation?		
1. Can additional necessary data be acquired prior to drilling by		
a. Geophysical surveys?		
b. Field investigations?		
c. Other techniques?	See Text.	Essential.
2. Are additional exploratory efforts justifiable in terms of the cost relative to the amount and quality of the data to be obtained?		
3. Can the same information be developed as part of the drilling program?		

monoclinal fold. It is particularly important from the point of view of enclosure to determine whether actual rupture of the formations has taken place. Seismic investigation may resolve this uncertainty.

More extensive seismic work may be necessary where there is very little subsurface control.

While it is possible to make generalizations regarding the character of the subsurface formations on the basis of their acoustical velocities as revealed from seismic records — to differentiate a porous low velocity material from a dense, high velocity material — seismic exploration is not well suited to detailed lithologic interpretation.

Seismic exploration is most effectively used to resolve structural problems in areas where the geology of the shallow subsurface is relatively understood and where the formations of the deeper subsurface are lithologically consistent over broad areas.

Other Geophysical Techniques

The number of other geophysical techniques is so great and their application to subsurface waste disposal so remote that consideration in detail is not justified in this report. Again, an experienced professional geologist will be able to recommend the appropriate techniques when special circumstances arise; for example, the use of resistivity methods to locate the subcrop of a critical aquifer.

Field Investigations

Many questions can be resolved by direct observation in the field.

Most subsurface rocks outcrop somewhere. It may be rewarding to examine and sample such outcrop sections. Care must be taken to avoid misleading data resulting from weathered samples or facies changes between the outcrop and the subsurface site. Surficial structure may yield valuable clues to the interpretation of subsurface data. Again, caution is indicated, since surface structure does not necessarily reflect that of the deep subsurface.

Aerial Photography and Remote Sensing

The interpretation of aerial photographs, particularly stereopairs, often reveals details of drainage patterns, subcrop and outcrop geology, and geologic structures which are not readily recognizable at the surface. Additional information may be obtained from special photography using selective filters and emulsions to enhance certain photographic qualities, such as infrared response. Of increasing importance, particularly in ground-water studies, is data obtained from satellite observation. Infrared scanning is particularly useful and may have applications in structural geology as well as in ground water.

Core Drilling or Stratigraphic Testing

The drilling of shallow wells to define structural relationships and the lithologic character of the shallow subsurface may be a valuable intermediate step prior to drilling full scale exploration and development wells.

Normally such programs are best considered as a downward extension of field investigations and are subject to the same limitations and cautions with regard to interpretation.

Drilling and Testing

It is important to recognize that the purpose of drilling is not simply to get a hole down to a specified depth. Each drilling operation should

Table 4. *The Drilling and Testing Stage*

INFORMATION REQUIRED	SOURCES	REMARKS
I. Objectives		
A. Stratigraphic information		
1. Depth and thickness of formations		
a. Reservoir		
b. Enclosure		
c. Observation and buffer		
2. Continuity and extent of units (by comparison with other well records)		
B. Structural information		
1. Attitude of formations		
2. Faults, joints, and fractures		
C. Reservoir information		
1. Effective porosity		
2. Permeability, magnitude and distribution		
3. Pressure		
4. Content (brine, oil, gas, etc.)	See end of Chapter.	Essential.
II. Initial exploratory well		
A. Drilling techniques		
1. Cable tools		
2. Rotary tools		
a. With mud		
b. With air or gas		
c. With foam		
B. Formation evaluation techniques		
1. Sample examination		
a. Cuttings		
b. Cores		
2. Geophysical logs		
a. Stratigraphic identification and correlation		
b. Porosity		
c. Fluid content		
d. Permeability		
3. Core analysis		
a. Reservoir		
b. Enclosure		
c. Observation zones		

Table 4 *(Continued)*

INFORMATION REQUIRED	SOURCES	REMARKS
4. Fluid production tests (before well completion) a. Cable tool holes b. Rotary holes C. Completion considerations D. Post-completion test 1. Pump test 2. Tracer surveys 3. Tests with effluent III. Additional drilling A. Exploratory 1. To confirm extent and continuity of critical formations 2. To further define structural anomalies 3. To ascertain variability in reservoir, enclosure, and observation zone fluid mechanical properties 4. To resolve any other questions B. Development 1. To gain greater injective capacity 2. To develop monitoring and control systems D. Spacing considerations 1. Interference 2. Coverage 3. Directional control	See end of Chapter.	Essential.

be considered as a geological experiment with the acquisition of information being a prime purpose (Table 4).

The means of obtaining information from a drilling operation are many and varied. The techniques actually employed, and in fact the drilling techniques themselves, will be largely dependent upon the type of information required. Thus, the drilling and testing program should be carefully planned according to the specific needs of the individual disposal operation.

The following paragraphs discuss some of the advantages and disadvantages of the more common drilling and formation evaluation techniques.

Drilling Techniques

The two basic methods for drilling of deep holes are cable tool and rotary drilling.

In general, cable tool drilling is relatively less expensive, provides good sample cuttings for examination and, if the hole is properly cased, provides a means for evaluating the fluid content of each successive formation penetrated.

Rotary drilling is becoming increasingly competitive with cable tool drilling in price, particularly when extensive casing is required in the cable tool hole. It is substantially more rapid and is adaptable to more testing methods than is cable tool drilling.

Sample Examination

Much fundamental geologic information may be obtained from examination of samples, either drill cuttings or cores.

Stratigraphic identification, formation contacts, estimates of porosity, and similar features may be determined.

1. For the examination of cuttings, cable tool samples are normally extremely reliable since their depth of origin can be accurately determined.
2. Cuttings from mud-drilled rotary holes usually include a substantial portion of cuttings from up-hole formations as well as from the formation currently being drilled. Some interpretative skills based on penetration rate, mud circulation time, and foreknowledge of the anticipated lithology are required.
3. Cuttings from gas- or air-drilled wells are subject to many of the same difficulties as those from mud-drilled holes, with the additional problem that the samples are commonly finely comminuted. Even more interpretive skill and experience is required for successful use of the samples.

Examination of cuttings does not provide reliable data on internal structures such as laminations, vugs, fractures, or joints, nor upon gross structural relationships such as angle of dip. For these purposes cores are preferred. While cores may be obtained in cable tool holes by percussive coring or rotary coring on tubing, such samples are not as satisfactory for examination as are large diameter rotary drilled cores.

Geophysical Logs

The wide variety of geophysical logs available provides a rapid, convenient, and relatively inexpensive method of acquiring general reservoir characteristics.

Since geophysical logs are comparatively common, they form a useful basis for correlation, not only of stratigraphic units but also of more specific reservoir characteristics.

Geophysical logs are subject to certain inherent limitations. The porosity measured from geophysical logs is *total* porosity, not *effective* porosity. Porosity determinations from geophysical logs are based upon a response to fluid content.

Only rather indirect conclusions regarding permeability can be drawn from geophysical logs.

A further consideration in the use of geophysical logs is the "zone of investigation." Again, with few exceptions, geophysical logs integrate the characteristics of a zone ranging from a little over one foot in thickness to approximately twenty feet. Similarly, the depth of investigation, the lateral penetration beyond the well bore, is quite variable. Thus, while useful in determining general or average characteristics, *most geophysical logs do not permit definition of thin geological features such as bedding relationships and fractures.*

With appropriate supplemental data, geophysical logs are a very useful source of fluid saturation data, particularly for oil and gas. In this application their extensive zone of investigation is superior to most other formation evaluation techniques.

Core Analysis

In addition to permitting detailed stratigraphic, lithologic, and structural data, cores are susceptible to direct experimentation to determine specific fluid flow characteristics.

Both effective and ineffective porosity may be determined, permeabilities to various fluids may be measured in any direction, and fluid content can be evaluated. Cores are also susceptible to mechanical testing to determine their compressive strengths and yield points.

The primary defect of core analysis lies in the small size of the sample compared to the volume of the reservoir to be evaluated. Except in the most uniform lithologies, the older and more common plug analysis can be greatly misleading unless great care is taken to select the plug

from a truly representative portion of each foot of core. Analysis techniques employing the whole core offer a substantial improvement over plug analysis.

One difficulty frequently encountered in the use of core analysis is in the interpretation of permeability data. For waste disposal purposes, permeabilities should be measured using water or the actual effluent as the flow medium.

Core analysis of extensive intervals is particularly useful for detailing the permeability profile of either the reservoir or "caprock." While the core analysis of a few representative samples provides useful general information, it fails to define specific zones of potential "breakthrough" or leakage.

The application of core analysis is not limited to reservoir evaluation. It is in fact virtually the only method of evaluating the caprock short of full scale pumping tests. Permeabilities to water of 10^{-6} millidarcies (one billionth of a darcy) are routinely made and the range can be extended further.

Evaluation of Fluid Content

Several methods are available for the determination of the character of fluid content, fluid pressures, and approximations of the permeability and volume of the reservoir.

In an unfilled cable tool hole there is a constant source of fluid samples and a source of pressure information by recording the static water level. Careful measurement of the rates of fill-up can yield data on the capicity or permeability of the formation.

The drawback of the cable tool hole in this connection is primarily the requirement that all up-hole water sources be cased or otherwise shut off. This is a complicated and costly procedure where many water-bearing formations are anticipated.

In rotary drilled holes, drillstem tests can be employed to evaluate potential fluid productive formations. This may be done either while the hole is being drilled or after the hole is completed. Analysis of fluid recovery, together with the pressure charts recovered with a drill-stem test, may provide useful information on the permeability, capacity, and reservoir size.

The major difficulty in using drillstem test techniques is in the recognition of those zones which ought to be tested. Particularly in a mud-filled hole, there is no means of recognizing fluid-bearing horizons as they are penetrated, so that if complete information is required, many "dry tests" must be performed.

Completion Considerations

The term *completion* refers to the final mechanical treatment of the well; that is, equipping it for use or plugging it for abandonment. In either event it requires careful evaluation, planning, and performance. If the well is to be used for disposal, the completion technique should provide for maximum efficiency and safety of operation. If the well is to be abandoned, it must be left in such a condition that it is not in itself an environmental hazard nor a hindrance to other uses of the subsurface.

If, upon completion of the drilling phase, it seems probable that the disposal project will be carried forward, there are a number of departures from standard oil field completion practice which should be considered:

1. A disposal well is inherently a permanent installation. It is desirable that it outlast the useful life of the project to provide a means of monitoring and control until all danger from the effluent has passed.
2. *Particular attention is required to the quality of the casing* and the thoroughness of the cementing program. Because the annulus between the casing and hole wall provides the obvious and potentially most damaging route for mechanical leakage, *full cementation is strongly recommended.* If cement cannot be circulated behind the full extent of the casing, it should be emplaced for several hundred feet above and below the injection horizon and opposite every permeable, fluid-filled formation.
3. The casing diameter should permit ready access, including the running of liners, in the event that remedial measures are later required. The relative merits of multiple completions may be considered. If the effluent is injected through tubing, and the annulus between the tubing and the casing used as an observation well, the casing will serve as a safety measure in the event of rupture or leakage of the tubing.

Unplugged or poorly plugged wells are a serious obstacle to all potential uses of the subsurface. They provide a direct flow-path through which saline waters can reach the surface or other shallower aquifers. They are in effect "a short-circuit" in the rock/fluid system and they contribute to the damage of other resources. *Ideally, if the well is to be abandoned, it should be plugged solidly from top to bottom with cement.* At the very minimum, cement plugs should be set opposite all permeable horizons and precautions should be taken to ensure a good bond between cement and the wall of the hole.

Post-Completion Tests

After the well is cased and before disposal operations are commenced, there is an opportunity for extensive testing of the proposed reservoir and the mechanical elements of the well itself. Water or inert gas may be injected or brine withdrawn; radioactive, chemical, or fluorescent tracers may be injected and monitored; and ultimately, minor quantities of the effluent may be injected for a final test of injectivity and chemical compatibility. The selection of these tests will depend largely upon the circumstances surrounding each project.

An extensive fluid withdrawal test is particularly useful. If there is no fluctuation in the pressure in the observation zones, there is good evidence of integrity in the enclosure. The advantage of withdrawal testing is that the volume withdrawn is available for the disposal of effluent without raising pressures above normal. Were injection testing used, pressures would have already been raised before the effluent reached the reservoir.

Actual waste injection should begin on a very gradual basis. Many possible harmful effects of disposal may take periods of weeks or months to appear. Initial injection rates should be extremely conservative and monitoring scrupulous (Table 5).

Table 5. *Post-Drilling Evaluation*

INFORMATION REQUIRED	SOURCES	REMARKS
I. Predisposal tests A. For injectivity B. For capacity C. For integrity	See end of Chapter.	Essential.
II. Pilot disposal operations	Results of monitoring and reevaluation.	Essential.
III. Operating data	Results of monitoring; injection records.	Essential.
IV. Post-disposal surveillance	Results of monitoring; fluid sampling.	Essential.

OPERATION AND ABANDONMENT

The transition from the last stage of development to full scale operation should be gradual. The disposal operator must recognize that, as the pressure front and the leading edge of the effluent radiate outwards, exploration and development are a continuous process.

When waste injection is begun into the deep subsurface, the operator immediately incurs an obligation. The requirements of knowing "what it is," "where it is," and "what it is doing" are not relieved until the project is both chemically and hydrodynamically inactive. This may be a period of months, years or decades after the cessation of injection. Depending upon the scale and type of disposal operation and upon the local geological conditions, it may be more difficult to abandon a disposal facility than it was to begin it.

General Considerations

The geological aspects of the operational phase are similar in most details to the development phase. Since the interaction with the rock/fluid system is continuous, the gathering of data must also be sustained. The project must be constantly reevaluated geologically as well as economically.

Dilution vs. Concentration

It is argued that subsurface waste disposal is less hazardous when the injected liquids are strongly diluted. In most cases this is incorrect.

Whether diluted or concentrated, the same *quantity of basic waste* is going to be injected. Since most of the problems which may occur are related to pressure and volumetric displacement, it is apparent that concentration is more desirable than dilution. Pre-injection concentration should be considered wherever possible. If dilution alone would render the effluent innocuous, there would be no need for subsurface injection. Since the intent of subsurface injection is to place the material outside of man's environment, there is no need to be concerned by the quality of the material. *Our concern should be with minimizing the effect by reducing the quantity of the injected effluent.*

Supervision

It is particularly important that careful supervision by well-qualified and responsible parties be maintained, because many of the potential effects of subsurface waste disposal are irrevocable.

There is a tendency in most waste disposal projects to extend their utilization to the disposal of materials other than those for which they were originally designated. Finally, in almost any kind of commercial endeavor there is a reluctance on the part of people responsible for an operation to report its failures and defects to their superiors.

Whether directed by industry or by a public body, continuous supervision of the geological and mechanical performance of a disposal well is essential.

The Effects of Time

As the system ages, a general deterioration of mechanical equipment will undoubtedly be anticipated. Similar deterioration in rock-related factors is also possible.

The bonding of casing to cement and cement to rock may break down with time. There is some evidence that a similar deterioration of integrity may take place in fractures or joints within the rock itself where they are subjected to repeated changes in stress. The joints may literally "work themselves open."

Prolonged exposure to acid effluents may dissolve certain formations, resulting in their collapse and subsequent slumping of superadjacent material.

There are several possible techniques for periodic inspection of the mechanical condition of the well and surrounding rock:

1. The so-called "bond log" measures the adhesion of cement to casing by the degree of acoustical coupling between the two materials.
2. The injection of radioactive tracers into the effluent followed by the scanning of the well bore with a gamma ray logging device can detect failures in the cement between rock and casing.
3. The above technique may be used in indicating the size of solution cavities developed in the vicinity of the well bore.

Special Considerations

Each waste disposal project will have its own special operating characteristics. These will have been recognized and anticipated if appropriate planning, exploration, and development measures have been taken. Certain general characteristics are associated with the two concepts of subsurface waste disposal.

The "Tank" Type of Disposal Facility

The permanent isolation, or "tank" type of disposal facility presents the least demanding requirements for operation and monitoring.

Quite literally, all that is required is to "fill the tank and then watch for leaks." This form of disposal, however, may demand the greatest

period of observation. It can be presupposed from the selection of this technique that the effluents contain hazardous characteristics of long duration. The monitoring of such a disposal site must be essentially a perpetual process so that prompt remedial measures may be undertaken if displacement of the waste fluids should occur.

The "Natural Treating Process" Type of Disposal

The majority of disposal operations will in all probability be of the temporary storage character. Since this approach to disposal depends upon progressive dispersal of the effluent, the monitoring requirements must also be progressive.

A normal monitoring system might involve five observation points, one above and one below the injection horizon, and three equally spaced observation points surrounding the injection well. If these observation points are to be satisfactorily sensitive during the early stages of injection, they must be located rather close to the injection site, at a distance of 500 to 600 feet. However, significant pressure increases may be noted in the observation wells within a relatively short time, a few weeks or months. Eventually the first traces of the effluent itself will appear. Obviously, new observation wells are required at this point.

As the circumference of the effluent-flooded area increases, the number of active observation wells may also increase depending upon the complexity of the local geologic environment. These wells should be drilled substantially in advance of the effluent front and principally in advance of the pressure front. They serve not only as observation wells but as further exploratory wells to permit the recognition of potentially unsafe conditions before damage occurs.

Abandonment

Ultimately, any disposal site must be abandoned. Abandonment may be the result of simply filling up the disposal reservoir, changes in the needs of the using industry, or the appearance of serious problems in the disposal operation itself. The need for abandonment may occur at any time, now or fifty years from now. Tentative abandonment plans should be made before operation is commenced so that they will be available in the event of an emergency.

In no case does abandonment imply only the cessation of injection. It requires a continued observation until pressures have equalized at a safe level, until the potentially harmful characteristics of the effluent have been attenuated, and until all wells have been satisfactorily

plugged. In an emergency, abandonment may require pumping of the well to reduce pressure and to remove as much of the injected effluent as possible. If the need for withdrawal is considered even remotely, suitable equipment and facilities should be in readiness, including pumps, lines, and places to dispose of the recovered liquids.

The plugging of wells may well be progressive, with some being abandoned while both pressure and effluent are still active; for example, the plugging of monitoring wells as the effluent front moves outward.

Whatever the reason and timing, it must be recognized that the technology of well plugging is one of the least developed areas of subsurface exploitation.

An improperly plugged hole is an invitation to interformational fluid movement. Extreme care is required, for such movements might be damaging.

Almost any oil-well driller can recite instances of reentering a previously abandoned well and either driving a cement plug to bottom or finding that it had already dropped to bottom under its own weight. In many of the older oil and gas fields it is not uncommon to find oil, gas, or water suddenly appearing in the vicinity of long abandoned wells. *A good plug must be mechanically bonded to the surrounding rock and consist of durable material.*

The experience of the oil industry with corroded casing, decomposing cement and similar problems is sufficient to justify exceptional precautions in the plugging of disposal wells. If the casing cannot be pulled, it should be perforated or ripped, particularly in critical zones adjacent to fluid-bearing formations. "Top-to-bottom" cementing is highly desirable. Where this is not feasible, a series of cement plugs may suffice. The emplacement of the plugs must be preceeded by a thorough flushing with clear water to remove mud, old cement, slime, and loose scale which might prevent a good bond.

Even after the plugging of the last injection well, a waste disposal project may not be completely ended (Fig. 13).

The duration, methods, and frequency of inspection required for subsurface waste disposal sites remain among the unanswered questions in this area of technology. To a large extent these decisions will have to be made with reference to the particular type of disposal and the character of the geological and human environment. The essential point once again is to recognize that the rock/fluid system is constantly and unpredictably active. Once a potentially harmful material has been emplaced within the earth's crust, we must keep track of it until it becomes innocuous.

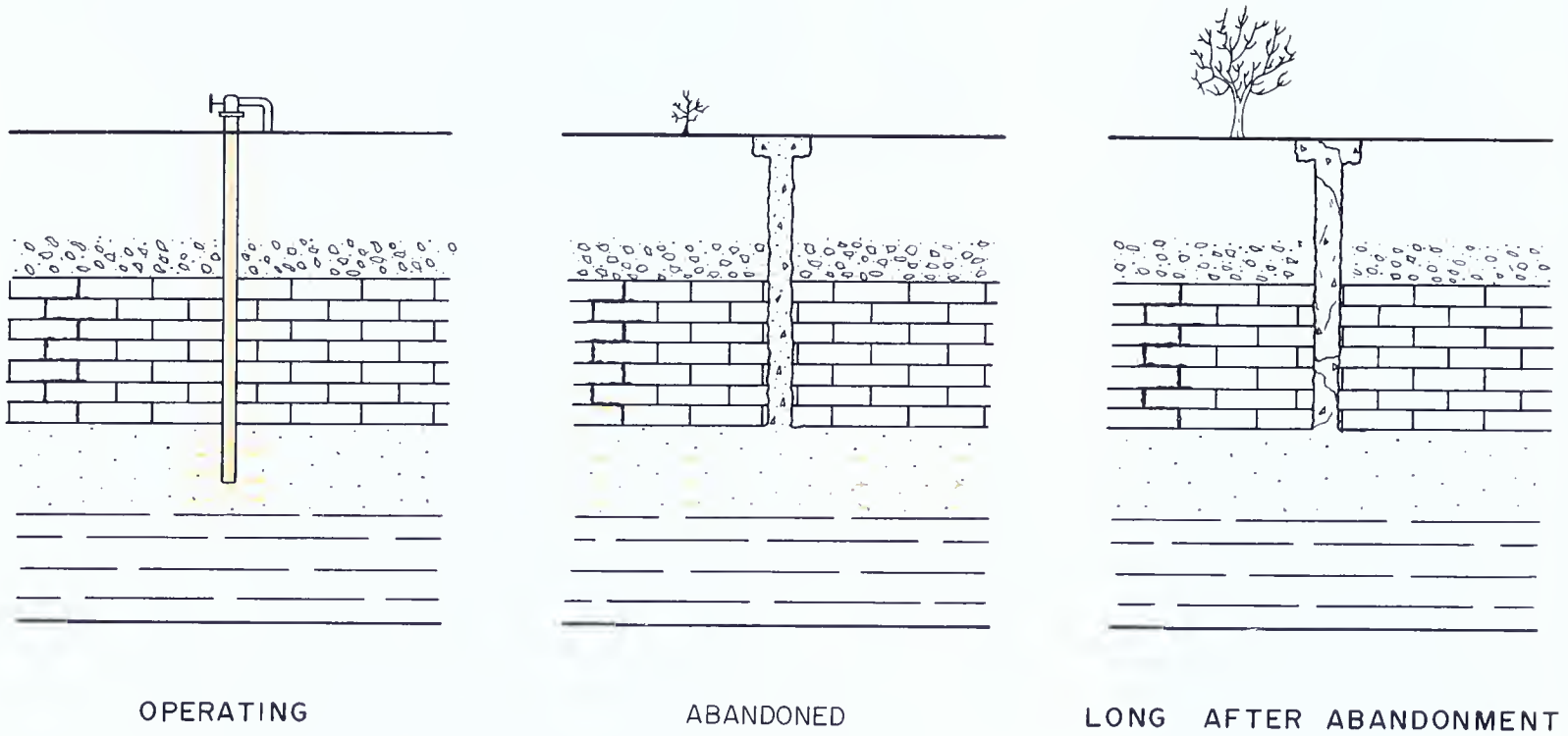


Figure 13. Disposal not completed when injection ceases.

PART III — OPPORTUNITIES FOR SUBSURFACE LIQUID WASTE DISPOSAL IN PENNSYLVANIA

The very complexity and variety of geologic factors which provide Pennsylvania with its great mineral wealth and its scenic beauty serve to limit its opportunities for subsurface waste disposal. Because of the extent and importance of the Commonwealth's mineral extractive industries, and because of the comparatively high population density within the Commonwealth, it is particularly important that the potential impact of waste disposal operations on the whole economic and human environment be considered.

The basic geologic requirements for subsurface liquid waste disposal include:

a) A reservoir, sufficiently extensive both vertically and laterally to accommodate the injected waste.

b) An enclosure, both hydrological and geological, adequate to constrain the flow of injected fluids in the desired directions.

c) A relatively simple, stable geologic environment susceptible to reliable and unambiguous interpretation and relatively free from the danger of alteration by man or nature.

Pennsylvania has few reservoirs of adequate permeability and porosity for feasible liquid waste disposal projects. Its structural geology is complex, creating difficulties in geological interpretation of the subsurface and producing a profusion of mechanical interruptions in rock continuity—faults, joints, and fractures.

Because of the complexity of the geology of Pennsylvania, it is particularly important that each individual disposal project be subject to extensive geological investigation. While the following portions of this publication will discuss general and regional aspects of the geology of Pennsylvania with respect to liquid waste disposal, this must not be taken as implying any less need for specific geological evaluation of each proposed operational location.

The purpose of Part III is twofold. The first is to delineate and classify the various provinces with regard to their prospects for disposal operations. In some areas the opportunities are so limited and the potential dangers so great that the investment of time and money in exploration for a disposal site is unwarranted. Other areas have more potential but present certain problems and difficulties which can be recognized in advance.

The second reason is to present general background data and suggestions as to the most fruitful areas and formations for further explor-

ation, together with warnings of some of the more evident potential dangers.

The user of the information contained in this part should be aware of certain limitations and biases in the data upon which it is based.

1. Direct quantitative measurements of the factors controlling fluid movement in rock in Pennsylvania are exceedingly scarce.
2. Such quantitative data as is available tends to be biased toward optimum reservoir characteristics, particularly when these data are derived from the oil and gas industry, whose activities are naturally concentrated in the areas of better reservoir development.
3. Much seemingly quantitative information is susceptible to misinterpretation and, in fact, such misinterpretations have been made in the past.

REGIONAL GEOLOGY

Physiographic Provinces

While the geology of much of Pennsylvania is quite complex, both structurally and stratigraphically, we may generalize by dividing it into four physiographic provinces, each of which trends northeastward across the state, and each of which has its own specific characteristics relative to subsurface liquid waste disposal.

Travelling northwestward from Philadelphia towards Erie one would encounter . . .

The Piedmont Province—gently rolling, highly eroded, ancient Precambrian rock and, slightly further to the west and north, some associated Ordovician and Cambrian rock of slightly more recent origin. These units are structurally complex and highly metamorphosed. On the extreme east margin of the Piedmont, extending a few miles northeastward and southwestward from Philadelphia, there is a thin veneer of relatively recent sands and gravels representing the westward margin of the Coastal Plain Province.

The Triassic Lowland – a narrow but thick band of sediments, characteristically reddish in color, which are the products of erosion following the uplift of the Appalachian Mountains in late Paleozoic time. These "detrital" rocks include shales, sandstones, and conglomerates deposited in a complex stratigraphic sequence and further modified by many intrusions of igneous material with concurrent and subsequent faulting.

The Valley and Ridge Province – the most readily recognizable province within the state, clearly displays the characteristic geological

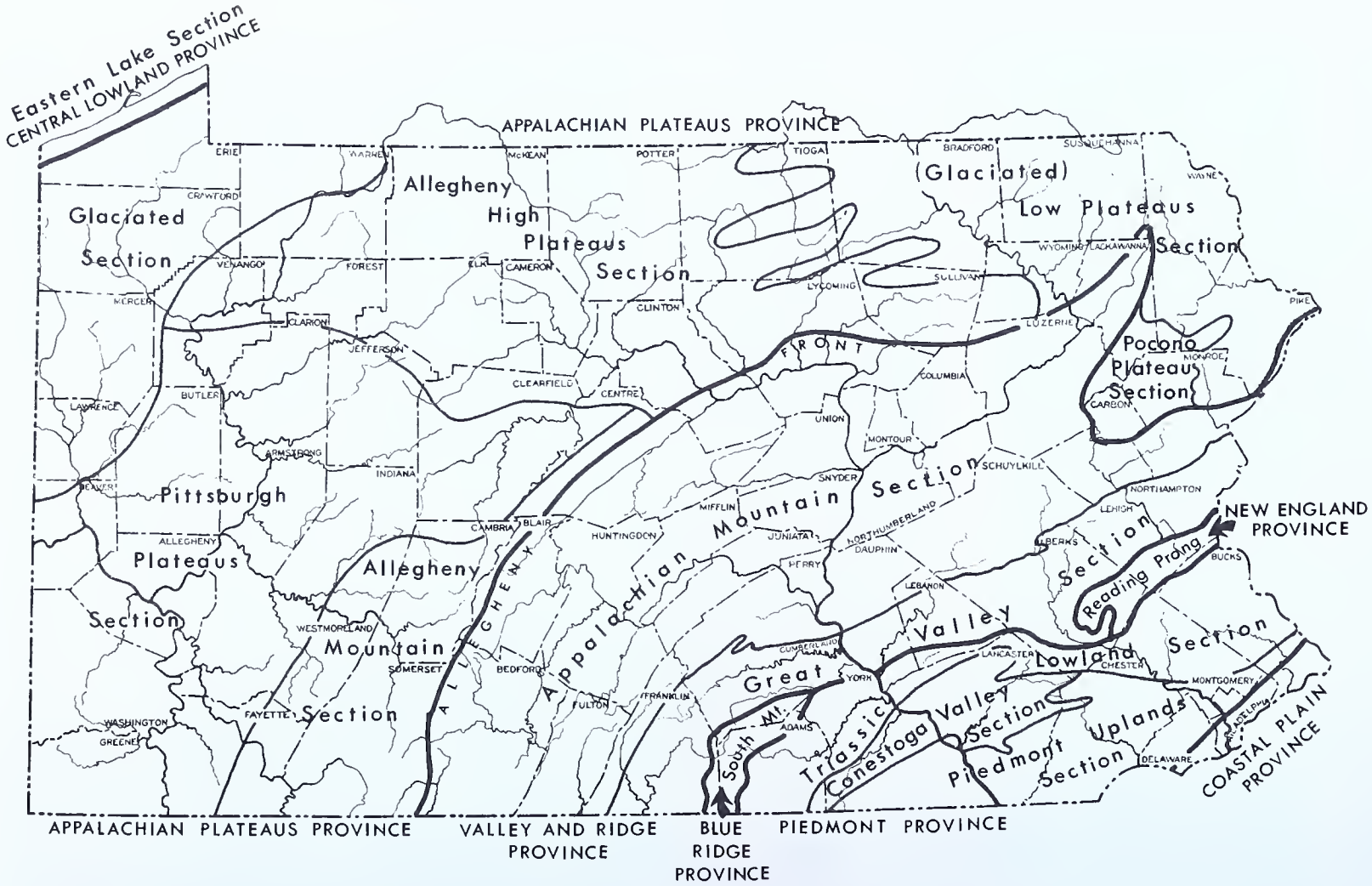


Figure 14. Physiographic provinces of Pennsylvania.

features, intensive folding on a large scale with associated faulting and fracturing. Paleozoic rocks of all types and all periods are involved in these massive contortions. They are frequently modified as a result of the immense pressures to which they have been subjected. The major effect of such metamorphism in connection with waste disposal is reduction of porosity and permeability. The intensity of deformation diminishes to the north and west and consequently so does the metamorphism of the rocks involved.

The Appalachian Plateaus Province — including the western and northern portions of the state and comprising roughly 60 percent of its area, is underlain by less highly deformed Paleozoic rocks, dipping generally to the east and southeast. This province with its thick sequences of comparatively unaltered sediments and more gentle and less complex structure offers the most favorable sites for subsurface liquid waste disposal.

Suitability for Waste Disposal

In reviewing Table 6 of the characteristics of the main physiographic provinces of Pennsylvania, it will be immediately evident that only the area of the Appalachian Plateaus can be classified as offering even moderately favorable conditions for subsurface liquid waste disposal.

This is not to say that the more easterly provinces may not contain some localized conditions which would permit the installation of small disposal facilities. Nor is it to say that the Appalachian Mountains and the Appalachian Plateaus regions can be uniformly considered acceptable. However, those undertaking to develop subsurface liquid waste disposal facilities in the Applachians and eastward must recognize that their exploration costs will be high and their opportunities for success will be low. Even in the more westerly regions, the sparsity of quantitative data indicates that extensive exploration and evaluation efforts will be required.

Since specific data on reservoir and enclosure quality is almost totally absent from the Appalachians eastward, and since a suitable disposal reservoir in these areas is not susceptible to identification by regional studies, no attempt will be made to further evaluate disposal feasibility in these eastern provinces.

THE APPALACHIAN PLATEAUS PROVINCE

The Shallow Sands

It is the practice of the oil and gas industry in Pennsylvania to group the sands of the Upper Devonian, Mississippian, and Pennsylvanian as the "shallow sands."

Table 6. *Characteristics of Physiographic Provinces of Pennsylvania*

	PIEDMONT	TRIASSIC LOWLAND	VALLEY AND RIDGE	APPALACHIAN PLATEAUS
RESERVOIR	Few porous, permeable zones in subsurface except in the Coastal Plain Province.	Numerous sand and conglomerate horizons of complex stratigraphy and uncertain extent and correlation. Little quantitative porosity and permeability data.	Occasional porous zones in formations, primarily in clastic rocks (sandstones and conglomerates). Quantitative data lacking except in potable ground-water zones. Porosity and permeability probably low with local exceptions.	Numerous potential reservoirs of Paleozic Age (Cambrian through Permian), many of considerable lateral and vertical extent. Modest amounts of quantitative data available suggesting relatively low permeability and porosity with local exceptions.
ENCLOSURE	Brittle, faulted, and fractured rocks make large enclosure unlikely.	Numerous shale members which may be lithologically adequate as enclosers. Continuity uncertain. Little quantitative data.	Several formations appear lithologically adequate but little quantitative data is available. Structural discontinuities (fracturing and jointing) are common.	Numerous formations which may be lithologically adequate for enclosure although quantitative data is almost universally absent (except in connection with oil and gas

				pools where the entrapment may be of capillary rather than lithological origin). Faulting, fracturing, and jointing present but less prevalent than in more easterly provinces.
STRUCTURAL ENVIRONMENT	Moderate to locally complex structural relationships, seismically stable.	Stable. Structurally complex due to faulting, intrusions, and difficult stratigraphy.	Structural environment stable but moderately complex.	Structurally relatively simple. Seismically stable except in extreme northwestern portion near Lake Erie.
OTHER COMMENTS	Very little information on subsurface below the depth of potable water.	Very little data available except where Triassic formations convey potable ground water.	Existing information relies heavily upon extrapolation from surface geology which may not accurately reflect conditions of reservoir and enclosure at depth.	Quantitative data of varying quality available in the vicinity of oil and gas fields. Data elsewhere is sparse.

This portion of the geologic section, comprising three to four thousand feet of sediments, will be considered as a single group in this report.

The stratigraphic position of the shallow sands is indicated in Figure 15. Their lithology and other factors concerning their suitability for disposal reservoirs are summarized in Table 7.

Because the shallow sands are relatively accessible and because they contain important resources, care must be taken that disposal operations do not bar access to fresh water, coal, oil, and gas. It should be noted that as much as two-thirds of the original hydrocarbon content may remain at field abandonment. It seems likely that society will eventually demand and technology provide a means for recovery of the remaining reserves. Field abandonment should not be taken as negating the value of the resources.

The shallow sands are in many respects the most desirable sites for liquid waste disposal in western Pennsylvania.

Reservoir Characteristics of the Shallow Sands

While the complex stratigraphy and high degree of variability of all the shallow sands make it difficult to generalize, experience from oil and gas production suggests that the sands of the Upper Devonian Conewango Group, the sands of the Mississippian, and of the Basal Pennsylvanian, may yield the best reservoir quality in terms of their porosity and permeability.

Porosities range to a maximum of more than 25 percent and permeabilities of more than 500 millidarcies have been measured. From geophysical logging data and the relatively few direct measurements by core analyses, it appears that a representative set of values, at least for oil and gas producing zones, is 10 to 12 percent porosity and 30 to 50 millidarcies of permeability. Grain sizes range from fine to coarse. The thicker sands may be quite free of argillaceous material, while the thinner units are often very shaly. Cementation is highly variable and commonly inversely proportional to the thickness of the sand body.

Major sands of the Mississippian and Pennsylvanian are often continuous over hundreds of square miles. Sands of the Conewango Group tend to occur in more sharply defined lenses ranging in area from a few acres to a few square miles.

The older groups of the Upper Devonian, the Canadaway and Conneaut, are generally deltaic in character, representing deposition from meandering distributary streams. These sands may be mixed with abundant argillaceous material. While occasional high porosity values (16 to 20 percent) have been observed, a more representative general

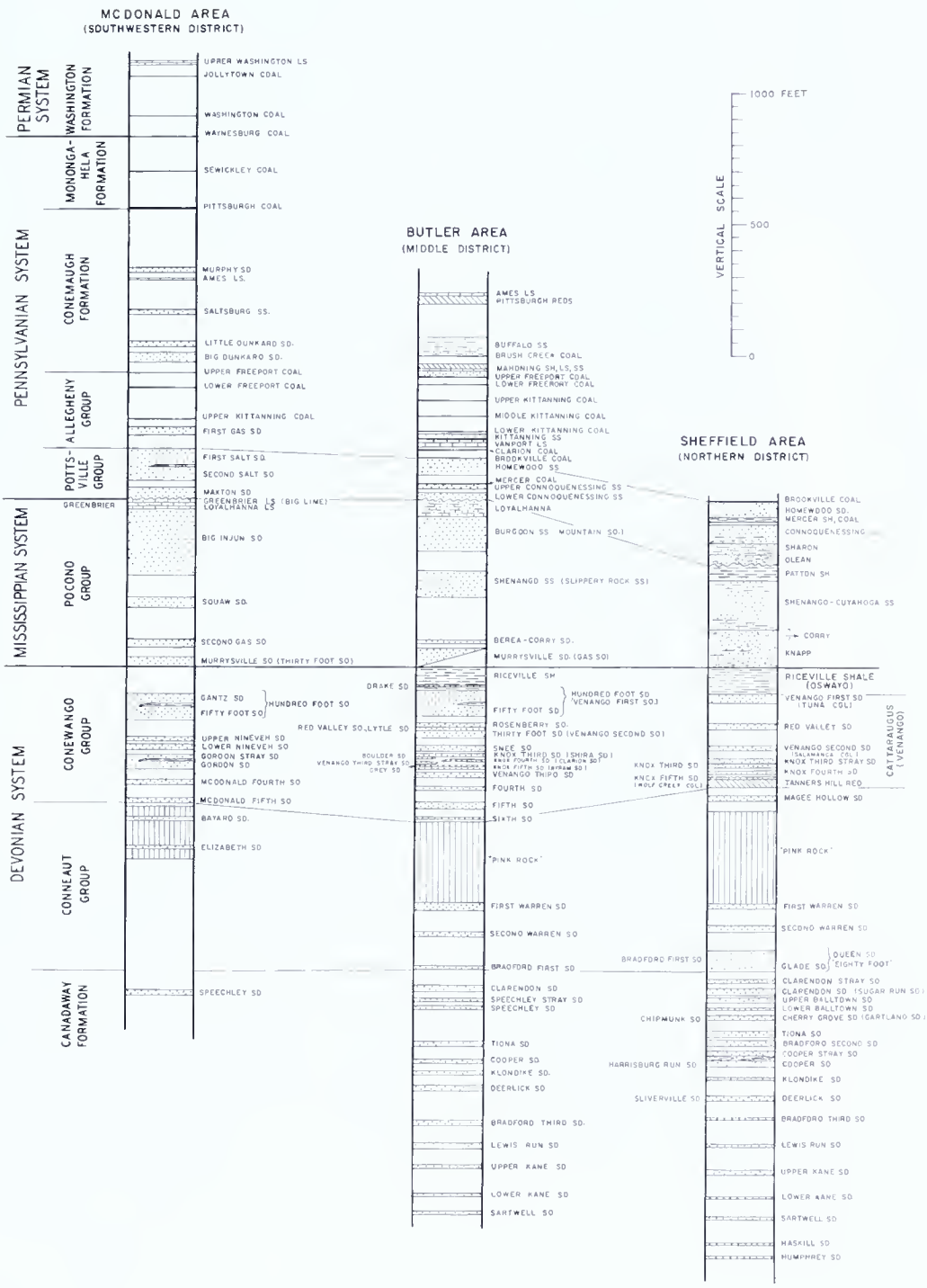


Figure 15. Stratigraphic positions of shallow oil and gas sands of western Pennsylvania.

Table 7. *General Geologic Section of Shallow Sands in North-Central and Western Pennsylvania (adapted from Lytle, 1963)*

	FORMATION	LITHOLOGY	RESERVOIR SUITABILITY
Mississippian	Mauch Chunk	Gray and red shale, subordinate, fine-grained sandstone. 0-100	Several massive and extensive sandstones in southwestern and western Pennsylvania may be disposal reservoirs. Character of lateral enclosure should be defined. Particular attention should be given to pressure depleted oil and gas field.
	Greenbrier	Consists in descending order of limestone, a shale break, and the Loyalhanna sandy limestone. 0-80	
	Pocono	Fine- to coarse-grained, massive sandstone and shale. Knapp sandstone and shale at base. Contains Big Injun, Squaw, Berea, Gantz, and Murrysville sands in southwestern district. 570-900	
Upper Devonian	Conewango	Gray shale and subordinate, fine- to coarse-grained light-gray sandstone; red shale, prominent in lower part in northern district; some purplish-red shale in middle and southwestern districts. Contains the Venango First, Second, and Third sands in the middle district; Gantz, Fifty-foot, Upper and Lower Ninevah, Gordon, and McDonald Fourth and Fifth sands in the southwestern district. Includes Chemung Formation. 3300-6000	Multiple potential disposal reservoirs except in extreme northwest. Sands often lensatic with probable good enclosure. Particular attention should be given to depleted oil and gas reservoirs.

Devonian — Upper Devonian	Conneaut	Gray and purplish-gray shale and sandy shale, subordinate sandstone. Contains the Bradford First or Glade sand in the northern district; Queen sand in the middle district; Bayard and Elizabeth sand in the southwestern district. Includes the Portage Formation.	Multiple potential disposal reservoirs in west and northwest. Sand bodies less well defined in deltaic and coalescing patterns. (Sands more fine-grained and argillaceous than Conewango Group with poorer permeability and porosity.) Lateral enclosure often uncertain. Depleted oil and gas reservoirs deserve attention.
	Canadaway	Gray shale and sandy shale, subordinate, fine- to coarse-grained, light-gray sandstone and fine-grained, chocolate-brown sandstone. Contains the Clarendon, Cherry Grove, Bradford Second, Cooper, Bradford Third Kane, and Haskill sands in the northern district; Speechley and Bradford sands in the southwestern district.	Several possible disposal reservoirs particularly in northwest. Reservoir quality may be poor and enclosure questionable due to erratic deltaic depositional pattern. Extensively exploited for oil and gas.
	Genesee	Gray shale and sandy shale, subordinate, fine-grained sandstone, dark-gray and black shale.	

value is 8 to 12 percent. The permeabilities reflect the fine grain size and admixture of clay material and average 5 to 10 millidarcies with occasional exceptions attaining permeabilities of 100 millidarcies. Where cementation and shale content are high, porosities may drop to 3 or 4 percent and permeabilities to 0.1 millidarcy and less.

The lateral extent of these reservoirs is often deceptively great. While a single oil or gas pool may seem to be defined, there are frequent indications of fluid communications through coalescent sand bodies over a much broader area.

Characteristics of the Enclosure

Most of the shallow sands are enclosed within geological sections in which shale predominates. *Vertical enclosure, both upward and downward, may be expected to be relatively good.* Similarly, the relatively sharply defined lensatic sands of the Conewango Group have a good probability of lateral enclosure. The extensive sands of the Mississippian and Pennsylvanian and the deltaic deposits of the earlier Upper Devonian groups are much more uncertain in their lateral confinement.

The most difficult aspect of the enclosure to evaluate in the shallow sands is the effect of the extensive oil and gas development to which they have been subjected. Literally hundreds of thousands of wells in Pennsylvania have explored the prolific oil and gas producing section of the Upper Devonian, Mississippian, and Pennsylvanian over a period of more than 100 years.

Regrettably, as a result of lack of foresight and inadequate regulation and supervision, many of these wells represent a severe impediment to waste disposal. Early wells were often plugged with no more than a cedar post driven into the top of the casing, leaving an open conduit for the migration of subsurface brines into the near-surface environment. Neither completion and plugging records nor exact well locations are available for a large proportion of shallow sand wells.

The geological records on the vast majority of shallow wells are wholly inadequate or lacking.

Deeper Formations

The deeper formations, those lying below the Tully limestone, contain a number of potential disposal reservoirs. This deeper section is portrayed graphically in Figure 16 and its characteristics with regard to waste disposal are summarized in Table 8.

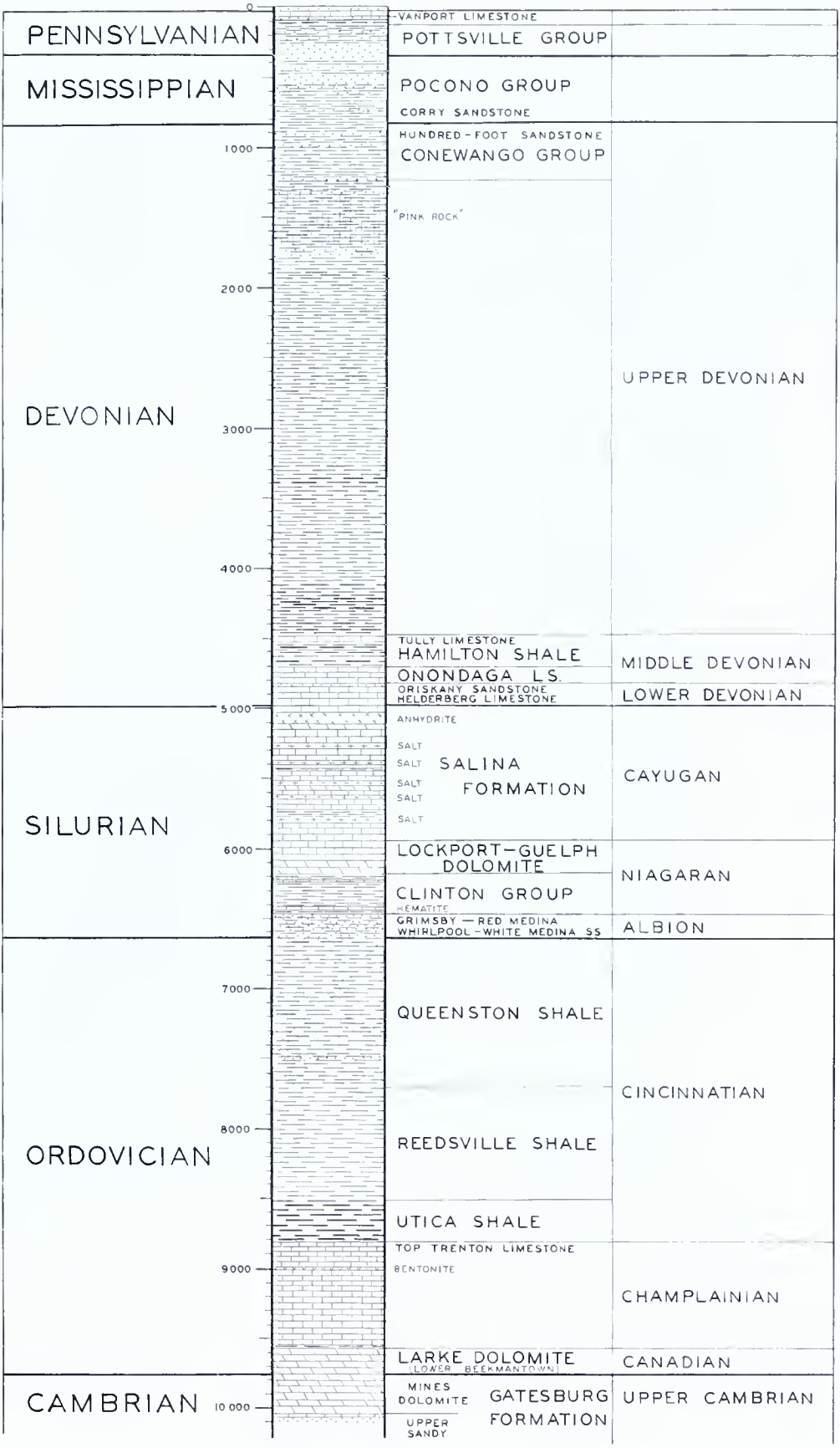


Figure 16. Stratigraphic positions of deeper reservoirs in western Pennsylvania.

Table 8. *General Geologic Section of Deeper Formations in North-Central and Western Pennsylvania (adapted from Lytle 1963)*

SYSTEM	SERIES	GROUP OR FORMATION	DESCRIPTION AND APPROXIMATE THICKNESS/FEET	REMARKS
Devonian	Middle Devonian	Tully	Argillaceous limestone. 0-150	
		Hamilton	Dark gray and black shale, in part calcareous. 100-2000	Generally good for vertical enclosure.
		Onondaga	Cherty limestone and chert, subordinate dark. silty shale and glauconitic beds. Source of gas in Clearfield, Indiana, Westmoreland and Fayette Counties. 8-290	Gas reservoir, where present, usually consists of fracture porosity. In northwest some evidence of intergranular porosity, — gas and water production.
	Lower Devonian	Oriskany	Medium-grained, quartz sandstone; locally calcareous; source of gas from north-central to southwestern Pennsylvania and in Erie County. 0-175	Adequate porosity (7-16%) in northwest. Local fracture porosity in folded belt to southeast. Major gas producing reservoir.
		Helderberg	Non-magnesian, in part cherty, frequently very fossiliferous limestone. 0-350	Occasional reports of water. Reservoir conditions generally unknown, but doubtful.
	Upper Silurian or Cayugan	Bass Island or Keyser	Argillaceous, dolomitic limestone. 20-450	Widespread salt-water zone near top, particularly in northwest. Occasional gas production near base. Site of apparently successful disposal at Erie.

Silurian	Upper Silurian or Cayugan	Salina	Interbedded, dense, argillaceous, magnesian limestone, gray shales, and calcareous or dolomitic clays. Numerous interbedded layers of anhydrite and salt. Small gas production in McCance field, Westmoreland County. 450-2000	Future potential for salt cavern disposal. (See Appendices.)
	Middle Silurian or Niagaran	Lockport	Very-fine, crystalline, brownish-gray to very dark-grayish-brown, relatively pure dolomite. A saltwater zone frequently present. Small gas production in Mercer County. 240-320	Extensively gas productive in reef facies in Ontario. Sulfurous saltwater zone in upper 150 feet is widespread in north and northwest. Little quantitative data.
		Clinton	Shale, dolomitic shale and subordinate dolomite. 100-300	
	Lower Silurian or Albion	Grimsby	Red and gray sandstone and shale. Gas and minor oil production in northwestern Pennsylvania. 70-220	The Medina sandstones of the subsurface—extensively gas and oil productive in Ohio and extreme northwestern Pennsylvania. Commonly very low permeability (<2 md) and porosity (<8%) but local exceptions noted in thick sand bodies.
		Cabot Head	Gray shale and subordinate, very fine-grained, light-grey sandstone. 70-220	
		Whirlpool	Fine-grained, light-gray sandstone. Minor gas production in northwestern Pennsylvania. 70-220	

Table 8 *(Continued)*

SYSTEM	SERIES	GROUP OR FORMATION	DESCRIPTION AND APPROXIMATE THICKNESS/FEET	REMARKS
		Queenston	Red shale, in part, silty and sandy. 850-1200	Of interest only as a factor in enclosure or disposal sites.
	Upper Ordovician or Cincinnatian	Oswego	Very fine-grained, gray sandstone. 0-60	
		Reedsville	Gray shale. 700-800	
		Utica	Black shale. 100-300	
	Middle Ordovician or Champlainian (and possibly Upper Canadian)	Trenton	Fine to very fine, crystalline, argillaceous, and fossiliferous, brownish-gray limestone; with interbedded dark gray to grayish-black, calcareous shale. At base is usually a 20′ to 50′ zone with a little interbedded, light gray bentonite or silty limestone. In Erie County, top 10′ to 15′ is dolomitic. Thickness increases from 250′ to 440′ in north to northwesterly direction. Greatest thickness in Erie and northern Warren Counties. 650-800	Occasional reports of salt water and hydrocarbons indicate existence of porous zones but reservoir quality seems doubtful.

Ordovician	Middle Ordovician or Champlainian (and possibly Upper Canadian)	Black River and Chazy?	Dense to very fine, crystalline, occasionally fossiliferous, light-brownish to brownish-gray limestone. In northwestern Pennsylvania the lower part contains interbedded dolomite and dolomitic limestone. Thickens from 275′ to 500′ in southerly direction. Greatest thickness in northern Butler and southern Mercer Counties. 650-800	
		Chazy? and Upper Beekmantown?	Silty and sandy dolomite and limestone in upper part; dolomitic shale and silty shale in lower part; with a dolomitic sandstone commonly found at base. Thickness 30′ to 150′; axis of greatest thickening in northeast-southwest direction through southern Warren, northwestern Venango, southwestern Crawford and northern Mercer Counties. 650-800	Occasional reports of salt water and hydrocarbons indicate existence of porous zones but reservoir quality seems doubtful.
	Unconformity		Approximately 4500 feet of Lower Ordovician strata present in central Pennsylvania are missing in western Pennsylvania.	
	Lower Ordovician or Canadian	Lower Beekmantown	Fine to medium-crystalline, siliceous, light-gray dolomite. Thickens in southerly and easterly direction from northwest corner of Pennsylvania. 0-190	Larke (Beekmantown) — Mines (Gatesburg) Zone frequently exhibits reservoir development by salt water flows and occasional gas where tested in western Pennsylvania. Little data available.

Ranging from 5000 feet of thickness in the extreme northwest to 25,000 feet or more in south-central Pennsylvania, this deeper section represents an immense volume of sediments which must be considered largely unexplored. Few wells have penetrated to a depth greater than 7000 feet. A very small fraction of the section has been tested to the extent of two penetrations per 25 square miles. Although the records of exploration of the deeper formations are substantially better than those of the shallow sands, they still leave much to be desired in terms of quantitative data regarding the character of both reservoirs and enclosures.

Certain potential disposal horizons are recognized from exploration, while a few others may be projected from existing geologic knowledge.

Oriskany Sandstone

Because of its importance as a gas producing reservoir, the Oriskany Sandstone is probably the best known of the deeper formations. Its reservoir characteristics fall into two quite dissimilar classifications.

1. *The Oriskany of northwestern Pennsylvania offers extensive reservoirs of intergranular porosity reaching a maximum of 15 percent and averaging 7 percent.* Permeabilities range from 10 to 50 millidarcies in the better porosity. (Permeabilities in excess of 100 millidarcies have been reported in rare instances.) The Oriskany of northwestern Pennsylvania ranges from 40 to 60 feet in gross thickness but the thickness of the net reservoir appears to be 10 to 20 feet out of maximum. Because of the prevalence of sulfurous salt water in the Bass Island underlying the Oriskany, most Oriskany wells of this area do not penetrate the full section. Accordingly, observations as to thickness are based upon extrapolation and surmise.
2. The Oriskany of the Allegheny Mountains relies heavily upon fracturing for its porosity. The granular porosity appears to be low. As would be expected in the presence of fracture porosity, permeability is often high, reaching values of several thousand millidarcies. Production records suggest that the porosity rarely exceeds 6 to 8 percent within the gas productive limits. Net reservoir thicknesses range from 5 to 35 or 40 feet. Precise thicknesses are difficult to determine with certainty because of partial penetration in many wells and because of evident miscorrelation with sandy, fractured zones in the base of the Onondaga in some areas.

The fractured character of the eastern Oriskany would seem to speak against its use as a disposal horizon; however, it should be pointed

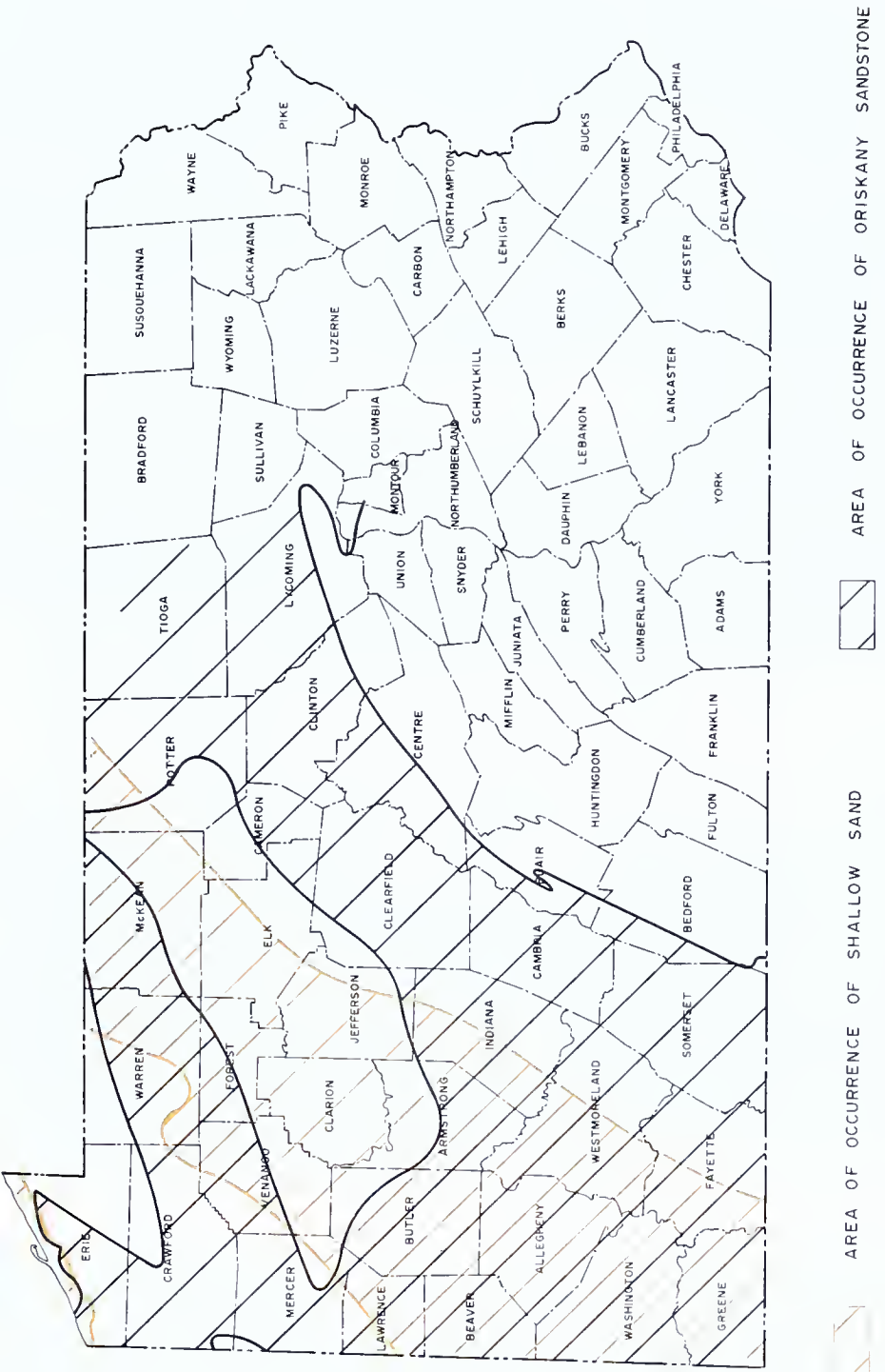


Figure 17. Distribution of known reservoirs.

out that the fractures in this reservoir are generally resealed by the deposition of calcite and silica. This sealing of the reservoir is in some instances so complete as to permit the retention of gas under pressures substantially above the local hydrostatic head. The presence of extensive fracture systems requires some caution in disposal facility design and operation. *It is likely, however, that the low porosity* commonly found in association with fractured reservoirs *will be more detrimental than the fractures themselves.*

Locally the overlying Onondaga Limestone, particularly in its more siliceous phases, has been found to be gas productive from associated fracture porosity. In most cases this appears to be simply an extension of the fracture reservoir of the Oriskany.

Bass Island (or Keyser)

Throughout western Pennsylvania and particularly in the northwest portion, the Bass Island sandy dolomite commonly produces salt water in a zone near its upper limit. The Bass Island is the site of apparently successful disposal operations at Erie, Pennsylvania (Hammermill Paper Company). Quantitative measurements of the reservoir characteristics of the Bass Island are almost lacking. However, the very prevalence of this water zone suggests that *the reservoir is extensive* and drillers remarks regarding "fill-up" rate together with the injection rates at Erie suggest that *its permeability and reservoir capacity are at least moderate.*

Lockport Dolomite

The Upper Niagaran Lockport carries a persistent sulfurous salt-water zone between 70 and 160 feet below its top. Shows of gas in measurable amount in fossiliferous, vugular dolomites have been noted throughout western Pennsylvania. The reef facies (Guelph) of the Upper Niagaran is highly productive in Ontario and may extend into northern Pennsylvania.

Little or no quantitative information is available on Lockport reservoirs. It should be noted that the overlying *Salina Formation with its thick salt beds provides a highly desirable element of enclosure should Lockport disposal prove feasible.*

The Medina Sandstones

The Lower Silurian Grimsby, Cabot Head, and Whirlpool sandstones are commonly referred to as the Medina and are extensively productive in northeastern Ohio and in northwestern Pennsylvania. Permeabilities

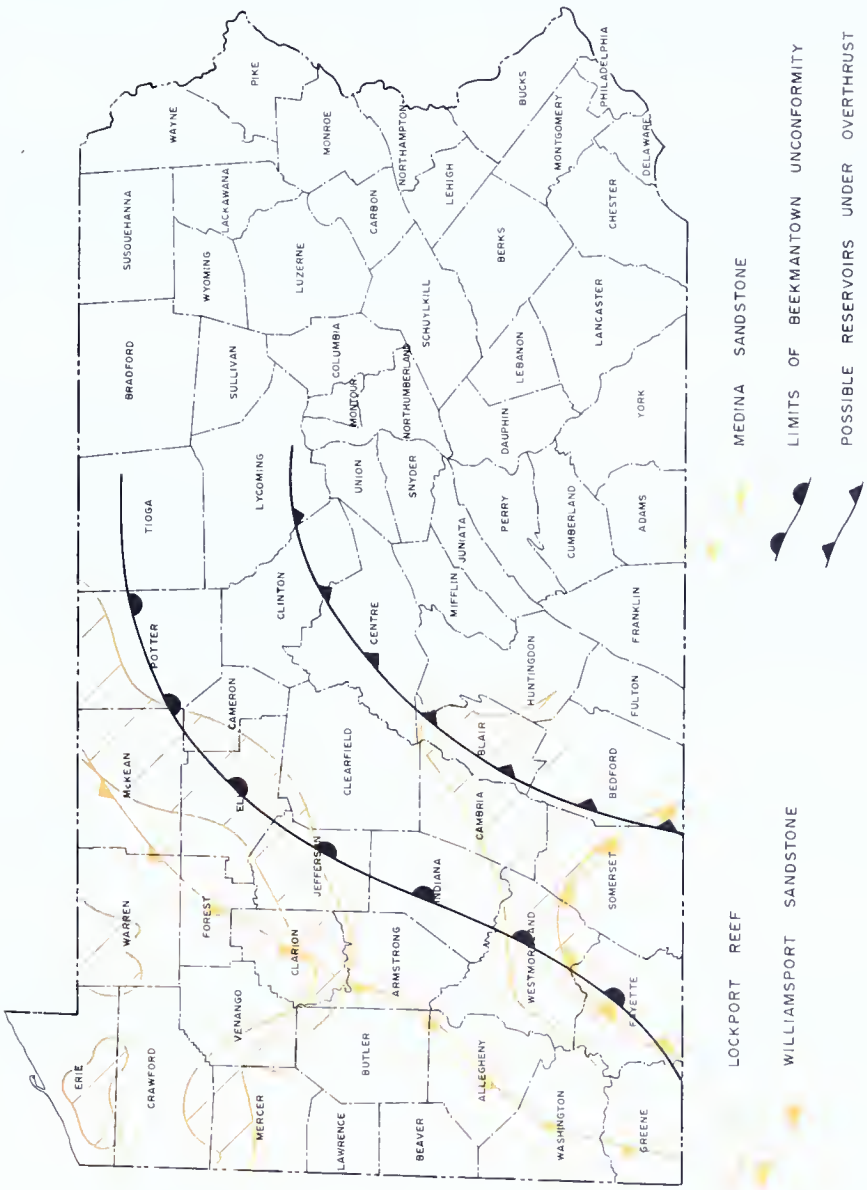


Figure 18. Distribution of possible reservoirs.

are very low, from 5 millidareies to less than 0.10, averaging less than 2 millidarcies. Porosities rarely exceed 8 percent, and average between 2 and 3 percent. Net reservoir thickness is normally less than 25 feet. As may be implied by the poor reservoir quality, the Medina Sands are eharaeteristically very fine to fine grained, extensively cemented, and interlaminated with shales. It seems unlikely that this formation will prove suitable for extensive disposal operations.

Trenton

The Trenton formation is very fine grained, dense, and often argillaeeous; however, oeeasional reports of salt water and minor quantities of gas indieate the existence of some porous zones. *The formation has not been widely penetrated but the development of an adequate reservoir seems doubtful.*

Larke-Mines (Gatesburg)

Beneath the Beekmantown unconformity in western Pennsylvania, the sandy dolomites and sands of the lowermost Ordovician and Upper Cambrian may be expeeted to have permeable, porous reservoir eonditions over broad areas. The primary porosities of the sandstones may be locally augmented by seeondary porosities developed in the carbonates as a result of weathering and solution during the period represented by the uneonformity. Wells in northwestern Pennsylvania have reported salt water and oecasional oil and gas from this interval. Very few tests have penetrated this zone. No quantitative data is available regarding the reservoir eharaeteristics.

The lower member of the Gatesburg is a sandy dolomite with interbedded sand phases. Before this horizon eould be eonsidered as a possible disposal horizon, mueh additional testing would be required.

Mt. Simon

The basal sandstone in western Pennsylvania has rarely been penetrated. It may be expeeted to be extensive and should be eonsidered as a potential disposal zone.

OTHER CONSIDERATIONS

Disposal Possibilities Other Than the Appalaehian Plateaus Provinee

In the Valley and Ridge Provinee the roeks at and near the surfaee are extensively altered. Formations whieh present good reservoir eharaeteristies outside this provinee are so redueed in porosity and perme-

ability as to be of no value for a disposal project. It should be noted, however, that the Appalachian Mountains have been overthrust westward upon a similar series of sediments near the margin of the Plateaus and the Valley and Ridge Provinces. These deeply buried rocks may be less disturbed and their reservoir qualities may have been retained. Should this prove to be the case, many of the deep formations discussed under the Plateaus Province may be considered as disposal reservoirs in this area of Pennsylvania.

In the north-central and northeastern portion of Pennsylvania, the Upper Devonian sands are largely replaced by the terrigenous red beds of the Catskill Delta. These rocks have received only minor exploratory attention since such lithologies are not considered favorable to the genesis and entrapment of oil and gas. The sands and conglomerates of this stratigraphic section should nevertheless receive consideration as potential disposal horizons.

Seismic Risk

Because of the attention drawn to the possible relationship between waste disposal at the Rocky Mountain Arsenal and a series of earthquakes at Denver, Colorado, some discussion of the relation between waste disposal and seismic hazard in Pennsylvania seems desirable.

Basically there are two questions with regard to seismicity: what will waste injection do to the seismicity of the area, and what will the seismicity of the area do to waste injection?

Effects of Waste Injection upon Seismic Stability

Compared to the Rocky Mountain front, the Appalachians are tectonically stable and are not subject to tectonic stress. If the earthquakes in the Denver area were the result of waste injection, it was a secondary cause, a "trigger," so to speak.

The Rocky Mountain Arsenal well injected effluent at considerable pressure into or near a fault plane. It is hypothesized that the effect of this injection was to wedge apart and lubricate the surfaces of this fault, thus permitting it to move slightly. It has been argued that, if stress was accumulating along the fault plane, earthquakes were inevitable and the effects of waste injection triggered an event which was already incipient.

The Appalachian Mountains have been tectonically stable for millions of years. In that they have a minimal history of seismic activity in recorded time, it seems unlikely that force imbalances exist which might be triggered by disposal operations. *Injection sites should avoid*

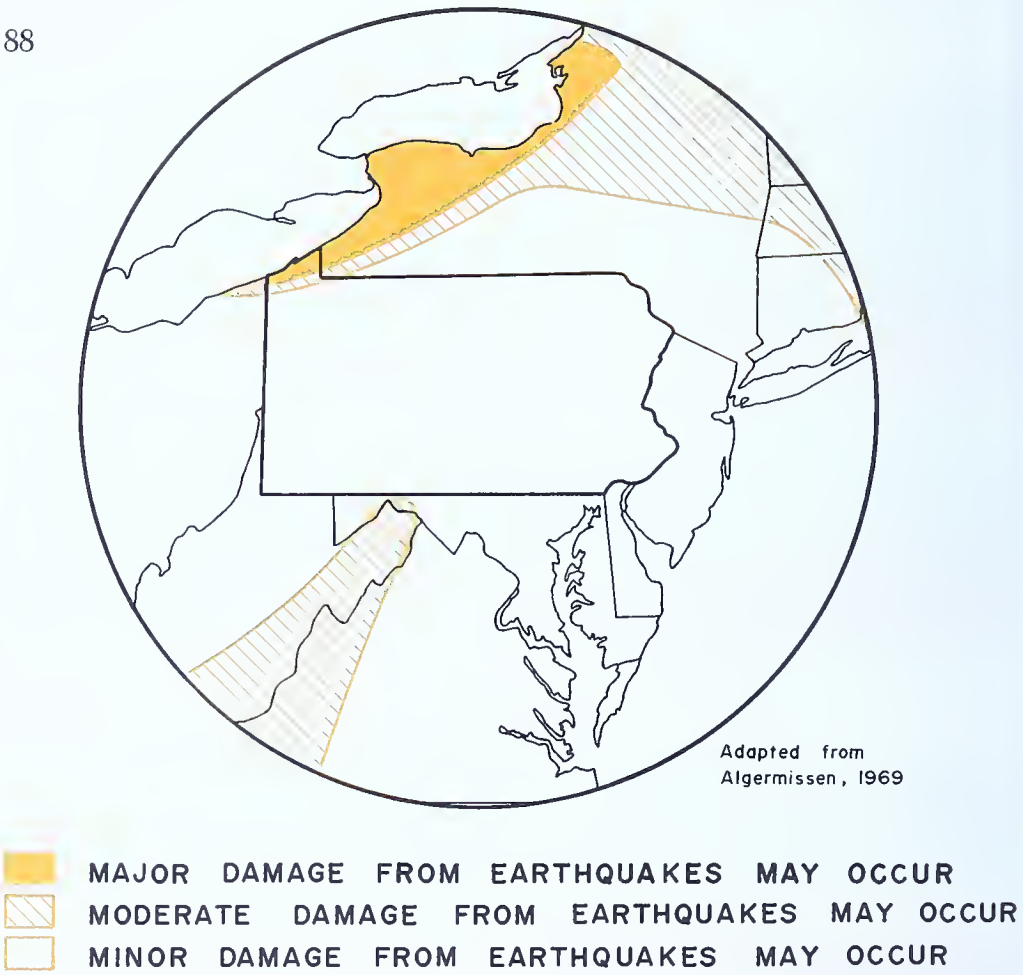

Adapted from
Algermissen, 1969
MAJOR DAMAGE FROM EARTHQUAKES MAY OCCUR
MODERATE DAMAGE FROM EARTHQUAKES MAY OCCUR
MINOR DAMAGE FROM EARTHQUAKES MAY OCCUR

Figure 19. Seismic potential in Pennsylvania and adjacent states.

known fault zones, however, because of the possibility of vertical migration of fluid through channels in addition to the danger of initiating seismic action.

The Effects of Earthquakes on Disposal Operations

A more important consideration in Pennsylvania is the potential effect of seismic activity upon disposal operations. Figure 19 indicates the seismic risk in Pennsylvania and adjacent states. The area of greatest potential damage from earthquakes is adjacent to Lake Erie.

Dangers from earthquakes are of two kinds: 1) structural damage to the mechanical equipment of wells; and 2) alteration of the rock/fluid system.

It is not uncommon for distant earthquakes to have significant effects upon fluid pressures in subsurface reservoirs. Often such effects are

transient, appearing or disappearing within a matter of minutes or hours. Occasionally, significant effects may persist for years or permanently. The Good Friday earthquake of 1964 in Alaska resulted in permanent alteration of several feet in the fluid height of a gas storage well in northern Illinois. Instances have been reported where water columns have varied by 80 feet, representing pressure changes of more than 30 pounds per square inch.

Under normal circumstances, such small changes relative to the total fluid pressures in a reservoir, would have negligible effect. However, the possibility of a seismically induced pressure change is an additional reason for conservative design in disposal operations.

The danger of mechanical disruption of injection facilities from earthquakes should be minimized by proper engineering design. These considerations should not be overlooked in the design phase.

CONCLUSIONS

Within Pennsylvania there are no known reservoirs of truly good disposal quality.

As a basis for comparison one may consider the Mt. Simon Sandstone of north-central Illinois which contains nearly 2000 feet of sand with porosity of the order of 15 percent, permeability to gas of the order of hundreds of millidarcies, and permeabilities to water which average approximately 50 millidarcies. This reservoir is continuous over thousands of square miles.

The well-known reservoirs of Pennsylvania are exceedingly restricted both vertically and laterally, their thickness measured in tens of feet and their lateral extent in tens or hundreds of square miles. Porosities are generally lower by half and permeabilities, even to gas, are characteristically a tenth as great.

It is very important that the full extent of this comparison be recognized since there is a strong tendency for non-geologists to assume that the rocks of the subsurface are generally similar from state to state and that what is done in one area may be done equally well in another.

The subsurface is a very real element of our environment and we must manage it wisely.

There are severe geological and man-made limitations on the use of the subsurface for disposal of liquid wastes in Pennsylvania. It is unlikely that subsurface liquid waste disposal will be widely employed in the near future due to the very high costs of adequate evaluation, operation, and observation which must be required if such injection is to be done efficiently and safely. Nevertheless there are opportunities,

now and in the future, for the disposal of industrial effluents in relatively small volumes where the need justifies the cost.

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APPENDICES

APPENDIX A

Legal and Regulatory Aspects of Subsurfaee Liquid Waste Disposal

A eomprehensive diseussion of the laws, prineiples, and regulations which may affeet waste disposal operations is clearly beyond the seope of this publieation. Those eoneerned with deep-well waste injeetion must investigate the legal aspeets of the project.

In addition to statutory and regulatory authority, eertain general prineiples of law may be eonsidered.

A fundamental and important question is the question of ownership and value of subsurfaec liquids, particularly brines. Fluids with monetary value or aeknowledged usefulness sueh as oil, gas, and fresh water have been the subject of legislation and litigation so that their ownership and evaluation is in little question. On the other hand, the brines of the deep subsurfaee have been of little interest or value in the past. Their status is not clear. In some areas brines have been produeed for the extraetion of soluble minerals. It appears that sueh operations have been conducted on the assumption that the law of capture applies and sinee the mineral rights to the property on whieh the withdrawal well is located are owned in fee simple or eonveyed by a mineral lease, the ownership has not been eontestcd. It may be presumed that the owners of adjaeent properties had at least the opportunity to proteet their interests by installing their own withdrawal operations if they felt there was any advantage in doing so.

In the ease of liquid waste injeetion the brine may be made nonreeoverable by displaeement from under a propcrty, by alteration of its ehemieal content through mingling with the injeeted effluent, or by limiting its aceessibility by inereasing pressures to a level requiring elaborate flow eontrol deviees or by so eontaminating the rescrvoir or its enelosure as to bar aecess.

In a strict theory of property rights, it might be argued that any alteration of the subsurfaee roek/fluid system without the consent of the owner, whether by aetual invasion by fluid or simply by elevation of pressure might be aetionable; however, in praetice it would usually be necessary to show that some damage had resulted. This is diffieult to establish. It is likely that litigation involving subsurface waste disposal would arise from pollution of ground water, from limiting aecess to other mineral resourees or, very rarely, from struetural damage due to movement induced in the roek itself (as for example, earthquakes).

Trespass, unauthorized entry onto the property of others, is the most evident basis for litigation. However, the elements of trespass, possession or ownership and intention on the part of the trespasser, are difficult to establish.

It is likely that litigation would be based upon allegations of negligence. It is further likely that the principle of *res ipsa loquitur* would be invoked. That is to say, the plaintiff would argue that the defendant had complete and absolute control over the injection operation responsible for the damage so that the burden of proof of sufficient care in design and operation should be shifted from plaintiff to defendant.

Nuisance, unlike negligence, does not depend upon the prudence or care of the operator of a disposal project, but rather upon his interference with the enjoyment or possession of the lands of another. Thus, without regard to the quality of design, installation, and operation of a project, it might be alleged that it was nevertheless a nuisance.

Similarly, the *doctrine of strict liability* may be invoked if it is alleged that subsurface fluid injection is inherently hazardous with respect to the rights of others. Under these circumstances a disposal project operator may be held responsible for damage despite the fact that he has not directly or materially contributed to the cause. If damage results from an earthquake initiated by waste disposal operations, the operator might be held liable for damages even though the earthquake resulted from accumulated stress on the rock which was unknown and unknowable to the operator and which stresses were released only as a secondary effect of the injection operation.

One may hypothesize many interesting legal questions. If one industrial plant injects its waste into a subsurface formation and elevates the fluid pressure, this elevation of pressure may bar an adjacent plant from installing its own injection system or require the use of costly drilling and completion procedures and abnormal power to pump the effluent in the already pressured formation. Is the first company responsible to the second company for the additional costs involved, or alternatively, may the first company take action against the second company for any increased costs borne by the first company as the result of the installation of the second injection system? Is the propagation of a zone of increased fluid pressure trespass, even when there is no direct invasion of extraneous liquid? Presumably such questions will be clarified by statute and case law. In the meantime, waste disposal operators should carefully evaluate their potential liability.

The question of interference between adjacent injection operations leads us to another area of concern, the public interest. The volume

of subsurface pore space available for liquid waste disposal is extremely great, but nevertheless, finite. Further, the industries which are the potential users of this disposal space tend to be concentrated in certain industrial centers. Therefore, it is not at all unforeseeable that interference between adjacent disposal projects may occur. May an industry producing a large volume of moderately nuisancesome effluent preempt a large proportion of the available disposal space to the partial or complete exclusion of another industry whose wastes, while small in volume, are far more undesirable or toxic?

A hundred years ago, or even fifty, most people would have felt it inconceivable that the Great Lakes could not dilute to the vanishing point all the human and industrial waste which could be spewed into them. Our lack of foresight in recognizing the finite limits of a resource has had tragic results. One can hope that the exploitation of a new disposal resource, the subsurface, can be accomplished with greater foresight and greater benefit to the public.

APPENDIX B

Some Alternative Approaches to Subsurface Waste Disposal

The scope of the present report has been limited to the injection of liquid wastes into previously existing pore space in the subsurface. There are several other ways in which the subsurface may be employed as a site for disposal. These techniques are restricted in their application, usually being limited to the disposal of particularly undesirable materials and requiring specific geological conditions. Brief descriptions are included below so that those interested in subsurface disposal may be aware of these alternatives.

Storage in Artificial Cavities

Certain minerals, notably salt and sulfur, are recovered commercially by solution. Mineral recovery of this character results in extensive solution cavities reaching hundreds of feet in height and thousands of feet in lateral dimension. These artificially created caverns may serve as disposal sites for finite quantities of waste liquid. No sulfur deposits of this nature are known in Pennsylvania. Extensive salt deposits do occur within the Salina group in northwestern and northeastern Pennsylvania, although they are not now commercially developed. It seems probable that salt producing operations will eventually be developed in Pennsylvania. Ultimately, this may result in the availability of large

caverns for disposal. Because of the "self-sealing" tendencies of thick salt deposits, it may be expected that the enclosure for these storage sites would be excellent. Unfortunately the capacity of the caverns is limited and the opportunities for imposing internal pressure greater than hydrostatic are limited by mechanical considerations. Another disadvantage of this type of a disposal site is the fact that, should the cavern be breached by some geological accident, the rate of liquid escape may be very great. Little opportunity for corrective action would be possible.

Grout Sheet Emplacement

In grout sheet emplacement waste material is mixed with cement and injected as a liquid or slurry. This mixture becomes immobilized within the rock by conversion to a solid. The volume occupied by the injected slurry is not natural pore space but is space created by the "wedging apart" of rock materials.

The advantage of this technique is that the injected materials are permanently isolated as a solid mass. The difficulties are its expense, the limited volumes which may be emplaced, and the rather specific geologic conditions under which such operations may be carried out.

Adsorption Into Shales

Shales may be highly compressed through geologic time and under the immense pressures created by tens of thousand of feet of overlying rock. This is indicated in the variation in porosity in shales, which may range from 40 percent or more for slightly compacted shales of recent origin in the Gulf Coast to 15 percent or less in the intensely compacted shales of the Appalachians. To an extent this compaction may be reversible.

A shale which has been buried at depths of twenty thousand feet and which has been uplifted or uncovered by erosion may have the capacity to re-expand. Under suitable conditions this may happen by adsorbing water by capillarity into the boundary areas between adjacent shale flakes. This phenomenon has been a source of considerable difficulty in some engineering designs where the stress state and fluid environment are altered. Conversion of this characteristic of shales to useful purposes, as a sponge to adsorb waste liquids, has been considered by various workers, including the present author.

The advantage of the technique is that the liquid is permanently immobilized by becoming a part of the solid shale formation. The difficulties are the location of suitable lithologic and structural condi-

tions and the low rates of injection per well which may be anticipated in view of the low permeability of shales. High injection pressures cannot be used because of the susceptibility of shales to extensive fracturing.

APPENDIX C

Measured Cap Rock and Reservoir Data

Explanation

Reservoir parameters discussed in this report are based in large part upon core analysis and geophysical log data obtained from the Oil and Gas Division of the Pennsylvania Geological Survey and from various oil and gas producing companies, consulting geologists and petroleum engineers. Some additional core samples became available for analysis in the course of this program and are reported below.

Of particular note are the measurements of vertical permeability to water of a number of samples representative of lithologies which may create the enclosure for disposal operations. While similar tests are routine in connection with gas storage operations in many parts of the country, no other data of this nature were found for Pennsylvania.

The number, geographic, and stratigraphic distribution of these samples are too small to justify their use without confirmation by extensive analysis in the immediate vicinity of prospective disposal operations. They may be useful in the formulation of preliminary judgements.

Cap Rock Samples

Vertical permeability to water was measured in Whole Core samples. In normal practice elaborate precautions are made to preserve the original liquid saturation in the samples. This was not possible in this case since the samples had been stored for long periods of time. Accordingly the samples were resaturated by evacuation of air to a pressure of 50 microns Hg, followed by immersion in water under 1000 psig pressure for 24 hours. Laboratory experience suggests that this procedure may result in permeability errors of an order of magnitude at a maximum. The measured value is usually smaller than the permeability in such cases.

Reservoir Samples

Tests performed on reservoir samples included the standard vertical and horizontal permeability to gas measurements. As noted in Part II

Table 9. *Water Permeabilities of Selected Pennsylvania Cap Rock Core Samples*

AGE	GROUP OR FORMATION	LOCATION	DESCRIPTION	PERMEABILITY TO WATER
Upper Devonian	Warren-Bradford Sequence	McKean County		
	Equivalent to Upper Pink Rock Zone		Gray-black shale	$<1.00\times10^{-8}$md
	Equivalent to Lower Pink Rock Zone		Gray shale	$<1.00\times10^{-8}$md
	Above Bradford #2		Gray laminated shale	$<1.00\times10^{-8}$md
	Top of Bradford #2		Gray-black laminated shale	3.24×10^{-3}md
	Between Bradford #2 and Bradford #3		Gray-black fossiliferous laminated shale	$<1.00\times10^{-8}$md
	Below Kane sandstone		Gray-black laminated shale	$<1.00\times10^{-8}$md
Middle Devonian	Hamilton Marcellus	Sullivan County	Gray-black shale	7.30×10^{-5}md
Lower Devonian	Onondaga	Beaver County	Gray-black cherty argillaceous carbonate	$<1.00\times10^{-8}$md
			Black chert argillaceous carbonate	$<1.00\times10^{-8}$md
Silurian	Medina	Ashtabula County (Ohio)		
	Between Irondequoit and Reynales		Gray calcareous shale	2.06×10^{-5}md
	Below Grimsby		Gray shale	3.16×10^{-5}md
Cambrian	Gatesburg	Erie County	Gray laminated cherty siltstone and slate	$<1.00\times10^{-7}$md

Note: Exponential notation of results may be converted to decimals by moving the decimal point to the left of the number of places indicated by the exponent, i.e., $1.0\times10^{-8}=.00000001$. The symbol "<" means "less than."

Table 10. *Core Analyses of Selected Pennsylvania Reservoir Horizon Core Samples*

Age	Group or Formation	Location	CONVENTIONAL CORE ANALYSIS: Vertical Permeability to Gas (Millidarcies)	CONVENTIONAL CORE ANALYSIS: Horizontal Permeability to Gas (Millidarcies)	CONVENTIONAL CORE ANALYSIS: Porosity %	PERMEABILITY TO NON-POLAR LIQUID (Kerosene): Vertical Permeability (Millidarcies)	PERMEABILITY TO NON-POLAR LIQUID (Kerosene): Horizontal Permeability (Millidarcies)	PERMEABILITY TO BRINE (30,000 ppm NaCl): Vertical (Millidarcies) Initial	PERMEABILITY TO BRINE (30,000 ppm NaCl): Vertical (Millidarcies) After 25 pore volumes thruput	PERMEABILITY TO BRINE (30,000 ppm NaCl): Horizontal (Millidarcies) Initial	PERMEABILITY TO BRINE (30,000 ppm NaCl): Horizontal (Millidarcies) After 25 pore volumes thruput	PERMEABILITY TO DISTILLED WATER: Vertical (Millidarcies) Initial	PERMEABILITY TO DISTILLED WATER: Vertical (Millidarcies) After 25 pore volumes thruput	PERMEABILITY TO DISTILLED WATER: Horizontal (Millidarcies) Initial	PERMEABILITY TO DISTILLED WATER: Horizontal (Millidarcies) After 25 pore volumes thruput
Devonian (Upper)	Venango First	Venango County		410.	17.4		270.			156.	114.			204.	136.
	Red Valley-Lytle	Venango County		63.2	18.2		36.8			24.6	22.5			30.4	25.7
	Bradford Third	McKean County	5.50	15.7	15.6	3.53	8.27	2.83	2.69	5.78	5.63	3.68	2.21	8.00	4.96
Devonian Middle & Lower	Onondaga (1st sample) and Oriskany	Beaver County (Plateaus Province)	<0.10	<0.10	3.3	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	2.9	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	2.2	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			5.43	29.6	6.6	1.76	10.7	1.03	0.98	4.21	4.37	0.72	0.41	3.61	3.29
			2.31	4.95	7.0	0.36	2.27	0.73	0.75	1.84	1.63	0.65	0.30	1.54	1.01
			4.83	8.35	7.9	0.87	1.26	1.39	1.43	0.83	0.81	0.16	0.70	1.92	1.74
			1.67	<0.10	4.4	0.23	<0.10	0.18	0.16	<0.10	<0.10	0.56	0.21	<0.10	<0.10
			<0.10	<0.10	4.5	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
	Oriskany	Bedford County (Folded Belt)	<0.10	<0.10	3.1	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	2.6	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	3.8	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	3.2	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	3.3	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	3.7	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	3.1	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10

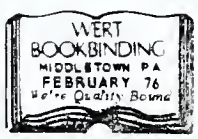
Table 10. *(Continued)*

Age	Group or Formation	Location	CONVENTIONAL CORE ANALYSIS: Vertical Permeability to Gas (Millidarcies)	CONVENTIONAL CORE ANALYSIS: Horizontal Permeability to Gas (Millidarcies)	CONVENTIONAL CORE ANALYSIS: Porosity %	PERMEABILITY TO NON-POLAR LIQUID (Kerosene): Vertical Permeability (Millidarcies)	PERMEABILITY TO NON-POLAR LIQUID (Kerosene): Horizontal Permeability (Millidarcies)	PERMEABILITY TO BRINE (30,000 ppm NaCl) Vertical (Millidarcies): Initial	PERMEABILITY TO BRINE (30,000 ppm NaCl) Vertical (Millidarcies): After 25 pore volumes thruput	PERMEABILITY TO BRINE (30,000 ppm NaCl) Horizontal (Millidarcies): Initial	PERMEABILITY TO BRINE (30,000 ppm NaCl) Horizontal (Millidarcies): After 25 pore volumes thruput	PERMEABILITY TO DISTILLED WATER Vertical (Millidarcies): Initial	PERMEABILITY TO DISTILLED WATER Vertical (Millidarcies): After 25 pore volumes thruput	PERMEABILITY TO DISTILLED WATER Horizontal (Millidarcies): Initial	PERMEABILITY TO DISTILLED WATER Horizontal (Millidarcies): After 25 pore volumes thruput
Silurian	Lockport	Mercer County	<0.10	920.	9.6	<0.10	233.	<0.10	<0.10	50.6	51.4	<0.10	<0.10	16.5	51.9
			0.88	<0.10	3.4	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
	Medina	Warren County	<0.10	<0.10	3.4	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	3.6	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	4.1	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	3.6	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	5.1	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			<0.10	<0.10	4.2	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
	Medina	Ashtabula County (Ohio)	<0.10	<0.10	6.2	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Cambrian	Gatesburg	Erie County	<0.10	<0.10	2.7	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			11.1	192.	13.9	2.77	24.8	0.18	0.20	2.38	2.34	2.64	2.71	37.5	47.0
			53.2	76.0	11.2	7.40	63.4	7.12	7.87	8.72	8.79	12.9	11.4	13.6	17.0
			<0.10	<0.10	2.6	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
			6.34	5.14	13.4	3.82	3.43	1.76	1.70	1.42	1.61	2.16	2.07	2.29	1.80
			2.05	1.33	12.6	0.94	0.76	0.66	0.69	0.45	0.40	0.73	0.79	0.65	0.49
			0.19	0.43	9.4	<0.10	0.43	<0.10	<0.10	0.18	0.18	0.96	1.02	0.36	0.28
			1.84	1.92	12.9	0.52	0.91	0.77	0.72	0.82	0.94	0.73	0.64	1.23	1.39

of this report, gas permeability values may be much greater than permeabilities to liquids due to the Klinkenberg effect and surface attraction of polar liquids. Accordingly, tests were also performed with a variety of liquids including brine, fresh water and kerosene. The latter liquid is non-polar and, in comparison with tests using water, serves to indicate the magnitude of surface activity effects.

All analyses were performed on plug-type samples (¾″ in diameter and 1″ long) due to the small size of the core fragments available. Since many of the samples were visibly heterogeneous the validity of individual test results when applied to the reservoir as a whole is questionable.

The fact that the majority of the samples reported here are of very low permeability does not necessarily indicate that such poor reservoir quality is universal in the formations sampled. On the contrary, where other analyses are available better permeabilities are often encountered. These samples appear to be, for the most part, "left-overs" after the better portions have been selected for further study and analysis by the operator. Their value is that they may indicate "average" rather than optimum conditions.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